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EFFECTS OF ACID MINE WASTES ON PHYTOPLANKTON IN NORTHERN ONTARIO LAKES

THE ONTARIO WATER RESOURCES COMMISSION

EFFECTS OF ACID MINE WASTES ON PHYTOPLANKTON IN NORTHERN ONTARIO LAKES

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SUMMARY

Studies were carried out during 1965 through 1967 on three Northern Ontario lakes; two (Quirke and Pecors Lakes) were contaminated by quantities of free mineral acidity from uranium milling wastes and one (Dunlop Lake) was unaffected.

Differences in chemical composition in the affected lakes, including low pH values and increased concentrations of SO_4^{-2}, NO_3^{-1} and Ca^{+2}, were directly related to processes in the extraction of uranium and subsequent treatment of wastes. Low concentrations of inorganic carbon in contaminated waters resulted from the reduced solubility of CO_2 and its loss during overturn and from the epilimnion during stratification. Other nutrients did not appear to be limiting since nitrates were in greater supply in the contaminated lakes than in Dunlop Lake, and phosphorus and silica occurred in similar concentrations in all three lakes.

Lower phytoplankton populations and indices of diversity were found in Quirke and Pecors Lakes than in Dunlop Lake. Many species of Bacillariophyceae, Chrysophyceae and Myxophyceae developed in the reference lake but were absent or occurred in extremely low numbers in the contaminated lakes.

Average primary productivities in Dunlop, Quirke and Pecors Lakes were 126, 71 and 34 mg C m^{-2} day^{-1}, respectively. In situ areal and volumetric measurements in laboratory and field bioassays confirmed the importance of inorganic carbon in limiting primary productivity. A potential compensatory mechanism in the contaminated lakes was a deepening of the euphotic zone. Although greater concentrations of inorganic carbon occurred and were assimilated in hypolimnetic waters, the mechanism was not sufficient to overcome the effects of reduction in species diversity and abundance of phytoplankton on the areal primary productivity.

It is concluded that inorganic carbon limits primary productivity in the lakes contaminated by acid mine wastes, with the reduced pH and inorganic carbon decreasing both the

number of species and total number of phytoplankton. Regeneration of inorganic carbon probably is impeded by acid conditions in these lakes and carbon is cycled inefficiently. Outside sources of inorganic carbon appear to be of extra importance to contaminated lakes.

The reduction in primary productivity in lakes affected by acid mine wastes will adversely affect higher trophic levels including fish and delay the removal of radionuclides to the deep sediments of the lakes.

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1.0 INTRODUCTION

Large deposits of uranium-bearing ore were discovered in 1953 in the Serpent River watershed on the north shore of Lake Huron. By the spring of 1958, approximately 35,000 tons of ore were being processed daily by acid leaching in 10 mills. One ton of solids and 2-5 tons of wastewater are disposed of per ton of ore milled. Small lakes and dyked swampy depressions are used to contain the solid wastes. The decant from these tailing areas flows to the large lakes of the Serpent River system.

The present study of phytoplankton communities and primary productivity was carried out in 1965-67 on two contaminated lakes and one unaffected lake. Although production of uranium had decreased by 1965, marked changes in the chemical and physical properties of affected lakes had already occurred, of which the decrease in pH appeared to be the most serious. Levels of radioactivity in lake waters, particularly of ^{226}Ra, were of public health significance. However, the increase over background levels to about tenfold in the most affected lakes, while possibly significant, was considered less important than gross chemical alterations affecting phytoplankton communities.

This report considers: differences in general physical-chemical limnology between contaminated and unaffected lakes during the period 1965-67, comparison of the specific composition and the seasonal and vertical distribution of the phytoplankton in 1966-67, and comparison of primary productivity in 1965-66. Attention is given to the manner in which excess free mineral acidity in mine wastes promotes the depletion of inorganic carbon and leads to virtual elimination of important components of the flora, which together affect primary productivity.

1.1 The study lakes

The Serpent River rises north of Dunlop Lake, flows from Dunlop to Quirke Lake where considerable mill waste water is received, thence east and finally south through Pecors Lake and several other lakes to the North Channel of Lake Huron (Figure 1). The watershed consists of outwash sands interspread with outcrops of pre-Cambrian igneous and metamorphic rock.

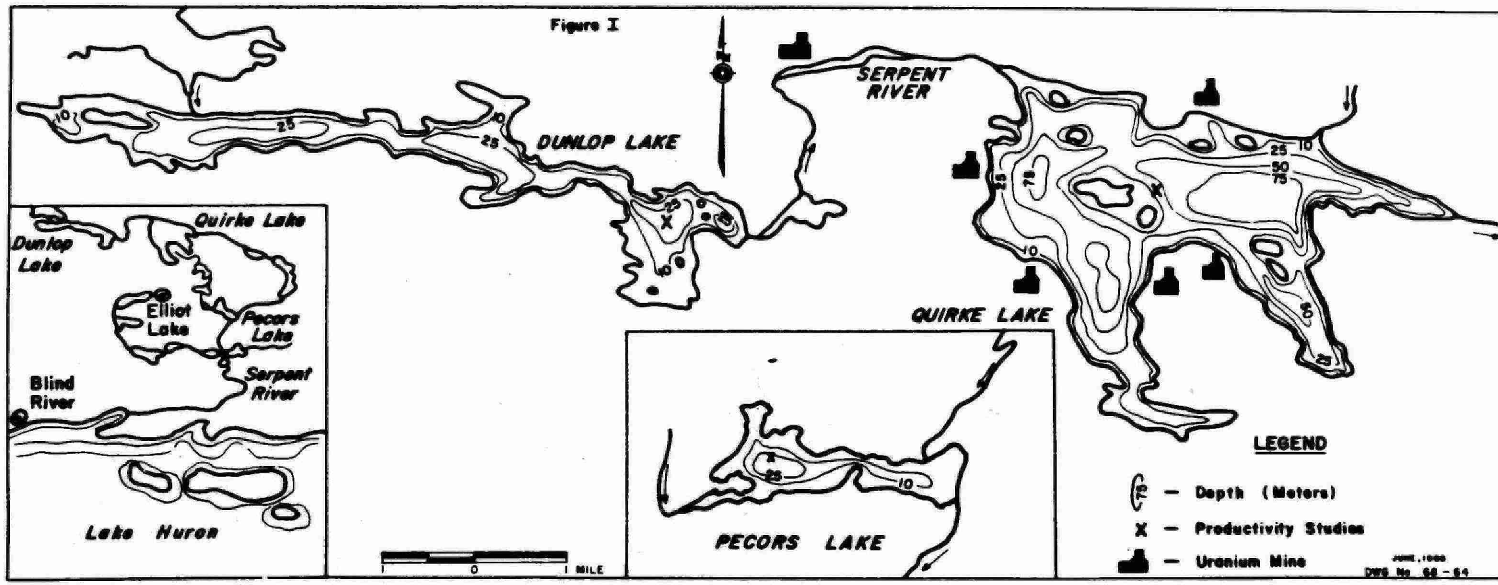


Figure 1 - Location of the study area on the north shore of Lake Huron (Inset) and sampling stations, uranium mills, depths of the three lakes examined.

Dunlop Lake is 2,020 acres (820 hectares) in area and 38 m deep. Samples were taken at a station of maximum depth in the eastern basin. No mill wastes have entered Dunlop Lake.

Two contaminated lakes were studied. Quirke Lake has an area of 4,600 acres (1,860 hectares) and maximum depth of 100 m. It is surrounded by six mills which processed approximately 20,000 tons of ore daily and much of the waste water from disposal areas entered Quirke Lake via the Serpent River. Water quality has been altered and comparison with Dunlop is logical because of its proximity and the fact that Dunlop Lake feeds Quirke. However, the morphometry of Quirke Lake indicates the possibility of sparser phytoplankton under natural conditions. Therefore, a second contaminated lake morphometrically similar to the eastern basin of Dunlop Lake was selected for study. Pecors Lake is 720 acres in area (290 hectares) and 40 m deep. In contrast with Quirke Lake, Pecors Lake receives flows displaced from contaminated lakes. Because the limnology of both lakes is influenced by characteristics of feeding lakes, Pecors Lake might be expected to be more susceptible to damage from acid mine wastes than Quirke Lake. The latter might be benefited at times of greater flow by waters received from uncontaminated Dunlop Lake.

2.0 METHODS

2.1 Physical-chemical

Temperature readings were made using a telethermometer. Penetration of light was determined with Secchi disc and, when available, a Gemware submarine photometer.

Water samples from the three lakes were returned to the Ontario Water Resources Commission laboratories for chemical analyses. All analyses were conducted following standard procedures. (A.P.H.A. et al 1965).

2.2 Collection and examination of algae

Phytoplankton samples were collected at centrally located stations (Figure 1) from six depths to 30 m in Quirke Lake and 23 m in Dunlop and Pecors Lakes. In 1966, samples were taken bi-monthly from March 31 through November 15 from Dunlop and Quirke Lakes and on three days (June 29, August 17, and September 28) from Pecors Lake. In 1967, bi-monthly samples were collected from the three lakes between May 16 and October 2. All samples were preserved with mercuric chloride at the time of sampling.

Because of the unproductive nature of the lakes, all samples were concentrated using the Sedgwick-Rafter sand-filtration technique (A.P.H.A. et al 1965). The use of sand together with silk bolting cloth with apertures of 25 u appeared to contain most of the nannoplankton, an important constituent of phytoplankton communities (Lund 1961, Goldman 1961). Changes in the seasonal and vertical composition of standing crops of phytoplankton were determined as numbers of organisms per ml using the Sedgwick-Rafter counting cell and a magnification of 200X. Also, standing crops of phytoplankton were measured in areal standard units (asu) for comparison with estimates of primary productivity. One asu is equal to an area subtended by 400 u^2. The areal unit was employed because it is as useful as cell volume and is preferred over cell numbers when relating primary productivity to standing crops (Paasche 1960).

Species composition was determined by examining permanent and semi-permanent slide mounts at 1200X. Permanent mounts were prepared using glycerin jelly as outlined by Pennak (1953). Identification of the Bacillariophyceae to the species level was facilitated by acid digestion of samples, following by mounting in either Hyrax or Mikrops mounting media. Taxonomic references included those of Prescott (1951), Patrick and Reimer (1966), Tiffany and Britton (1952), Smith (1950) and Sieminska (1964).

2.3 Diversity in phytoplankton communities

Diversity, or species variety relative to the total number of individuals, generally will decrease in a plant or animal community as environmental conditions become more adverse.

The index of diversity, I, (after Margalef 1958) for each depth on each sampling date for the three lakes was calculated from the equation,

$$I = \frac{S-1}{\log_e N}$$

where S is the total number of species and N is the total number of individuals. The mean index based on 5-6 samples from different depths was taken as the arithmetic mean of I.

Margalef's I is assumed to be independent of the numbers of individuals examined. Development of I using cumulative counts of algae indicated that this assumption was correct, provided that at least 50 individuals were examined. Sample I's in the present study were based on counts of between 50 and 375 individuals.

2.4 Primary productivity

Estimates of primary productivity were made concurrently in Dunlop and Quirke Lakes using the ^{14}C method on three days in 1965 (June 17, August 10 and October 2) and on three days in 1966 (June 14, August 3 and September 28). Estimates in Pecors Lake were made on June 29, August 17 and September 28, 1966.

Samples of lake water were collected at dawn in Van Dorn bottles from six depths down to 30 m in Quirke Lake and to 23 m in Dunlop and Pecors Lakes. In 1965, deeper samples taken from the former two lakes were found to be below the compensation depth. Water from each depth was dispensed to two clear and two dark (opaque) glass-stoppered bottles. $NaH^{14}CO_3$ was added to each (New England Nuclear Corp.; 100 ugm in 1.0 ml with activity of 10 uCi). The bottles were suspended for 6-9 hours at the depth from which the water was collected. Activity was arrested by adding mercuric chloride and within several hours the algae were removed on 0.45 u Millipore filters using moderate pressure (75 cm Hg). Each filter was rinsed with distilled water, dried and placed in scintillation-counting medium of 0.01% POPOP (1,4-bis-2-(5-phenyloxazolyl)-benzene) and 0.4% PPO (2,5 diphenyloxazole) in toluene. At the Industrial Hygiene Laboratories of the Ontario Department of Health, the ^{14}C activity of algae was determined with a Packard Tricarb spectrometer.

The use of mercuric chloride was investigated by comparing the activity of preserved algae with other subsamples which were filtered at the end of incubation. Although the preserved algae usually had slightly lower specific activity, the difference was within the limits of precision of the overall method.

The possibility of underestimating assimilation of ^{14}C, because of the loss by excretion of assimilated activity, was investigated. Filtrates were saved from 16 field analyses of ^{14}C assimilation, representing both light and dark samples from the epilimnion and hypolinmion of Quirke and Dunlop Lakes. No evidence of significant excretion of assimilated ^{14}C was obtained when subsamples of filtrates were acidified, stripped of inorganic carbon by bubbling with nitrogen and their residual ^{14}C activities (organic carbon) determined by scintillation counting in dioxane-napthalene with PPO and POPOP.

Calculation of inorganic carbon based on pH and direct titration of alkalinity was not advisable because of the small amount present. Therefore, duplicate analyses were carried out by distillation of inorganic carbon at low pH into 0.02 N NaOH in a closed recirculating system. The base

was titrated with 0.05 N HCl. The titre was corrected using "blank" determinations on samples of freshly-boiled, distilled water. Because this procedure led to delay in analyses, samples were preserved immediately after collection with mercuric chloride and the pH was adjusted to 8-9 with barium hydroxide.

The uptake of carbon by phytoplankton was calculated as:

$$1.05 \frac{Y}{Z} \cdot (W + Z) \text{ mg C m}^{-3}$$

where 1.05 corrects for isotopic discrimination (Strickland 1960), Z is activity of inorganic carbon added, Y is activity of filtered phytoplankton corrected for dark-bottle assimilation and W is inorganic carbon concentration in lake water (mg C m^{-3}).

Duplicate analyses of productivity based on independent measurements of light-bottle and dark-bottle activities and inorganic carbon showed a coefficient of variation ($s.100/\bar{x}$) of 20% in data from Quirke and Dunlop Lakes. Greater relative variation in analyses of inorganic carbon at the low concentrations in Quirke Lake (1 mg C l^{-1} and less) compared with Dunlop Lake (2 mg C l^{-1}), caused generally poorer precision in estimating primary productivity in the former. Precision in ^{14}C counting was similar in the two lakes. Estimates of productivity in Pecors Lake should be within similar limits.

The hourly rate of carbon assimilation on an areal basis was integrated graphically. Daily assimilation was based on the proportion of the day's isolation received during the incubation period.

2.5 Bioassays

Bioassays of possible limiting nutrients were conducted in the laboratory in 190-ml bottles and in the field in large polyethylene bags. The responses of phytoplankton to increased inorganic carbon and phosphate and to the two nutrients together were examined.

The polyethylene bags set in Quirke and Dunlop Lakes in early August, 1966, were 3.2 m long and contained 1 m^3 of water when set. One received 6 mg C l^{-1} as $NaHCO_3$ (which raised the pH of Quirke water to 6.7 but did not significantly change the pH of Dunlop water). The second received 0.2 mg PO_4 l^{-1} as $Na_2HPO_4 \cdot 12\ H_2O$, the third received both nutrients and a fourth bag served as a control. After several hours samples were drawn from each bag at mid-depth and duplicate light-bottles were set up and treated as described previously.

Duplicate samples of Quirke and Dunlop Lake waters were incubated in the laboratory at approximately 10 klux for 5 hours with ^{14}C and additions of 0.0, 1.5, 3.0, 6.0 and 9.0 mg C l^{-1} with and without 0.2 mg PO_4 l^{-1}. As in the field experiments, $NaHCO_3$ and $Na_2HPO_4 \cdot 12\ H_2O$ were used.

3.0 PHYSICAL-CHEMICAL CHARACTERISTICS

3.1 Ionic description

Dunlop Lake is typical of uncontaminated lakes in the pre-Cambrian Shield of Northern Ontario. Quirke Lake and Pecors Lake have undergone marked changes in chemistry, assuming that their ionic composition prior to mining activity resembled that in Dunlop Lake. Comparative data on the ionic constituents of the lakes are provided in Table 1.

Levels of calcium, magnesium, sodium, potassium, sulphate, chloride and nitrate increased from Dunlop to Pecors Lakes. Most of this increase is composed of SO_4^{-2} and Ca^{+2}.

The possibility that levels of heavy metals might have increased in lakes affected by mine wastes was investigated. Concentrations of soluble iron (0.03 mg l^{-1}), copper (0.02 mg l^{-1}), zinc (0.05 mg l^{-1}) and lead (0.04 mg l^{-1}) in Quirke Lake, although greater than in Dunlop Lake, did not appear to be extraordinarily high.

3.2 Inorganic carbon and pH

Lakes of the Serpent River system are naturally poorly supplied with inorganic carbon as shown by Dunlop Lake (Figure 2). This reference lake showed the progressive depletion of inorganic carbon in the epilimnion and regeneration in the hypolimnion during the summer. Quirke Lake had a lower concentration of inorganic carbon than Dunlop Lake. Inorganic carbon in Quirke Lake was erratically distributed with depth, although the surface concentrations were usually extremely low. The few analyses of inorganic carbon from beneath the euphotic zone in Quirke Lake indicated that the lower hypolimnion was as poorly supplied as the upper. However, this was to be expected in a lake of such great depth (as was the orthograde oxygen distribution regularly observed in Quirke Lake). Pecors Lake, which is morphometrically comparable to Dunlop Lake had similar concentrations of inorganic carbon in the hypolimnion, but Pecors Lake twice showed very low concentrations in near-surface waters, and in this respect, resembled Quirke Lake.

TABLE I. Summary of major ionic constituents (expressed in mg l^{-1}) and total dissolved solids in samples from Dunlop and Quirke Lakes in 1965, 1966 and 1967 and from Pecors Lake in 1966 and 1967. All ions were measured directly by analysis except HCO_3^{-1} which was calculated from total inorganic carbon and pH using the molecular proportions of total free CO_2 and HCO_3^{-1} (Hutchison, 1957).

Cation-Anion	Dunlop Lake			Quirke Lake			Pecors Lake		
	Mean	Range	No. of Analyses	Mean	Range	No. of Analyses	Mean	Range	No. of Analyses
Ca^{+2}	4.1	2.0- 7.8	86	38.1	34.0-54.0	85	66.5	38.0- 91.1	52
Mg^{+2}	5.0	0.0-10.0	13	5.4	2.0- 9.0	13	6.6	3.0- 14.0	6
Na^{+1}	0.5	0.2- 0.9	14	5.1	3.9- 6.9	14	6.8	6.0- 8.0	6
K^{+1}	0.5	0.3- 0.9	14	5.3	4.2- 6.1	13	8.6	7.0- 11.0	66
SO_4^{-2}	7.1	0.0-26.1	66	105.8	72.0-221.0	83	163.4	92.0-252.0	45
Cl^{-1}	3.1	1.0-12.0	44	6.9	5.1-15.0	42	10.7	7.1- 19.0	24
HCO_3^{-1}	6.5	2.5-11.5	72	0.5	0.1- 1.3	72	2.3	0.4- 3.6	30
NO_3^{-1}	0.4	0.0- 2.0	73	11.6	2.8-22.0	80	12.8	4.4- 30.0	48
Total Dissolved Solids	23.5	2.0-72.0	82	197.4	73.1-410.0	88	339.0	99.0-499.1	48

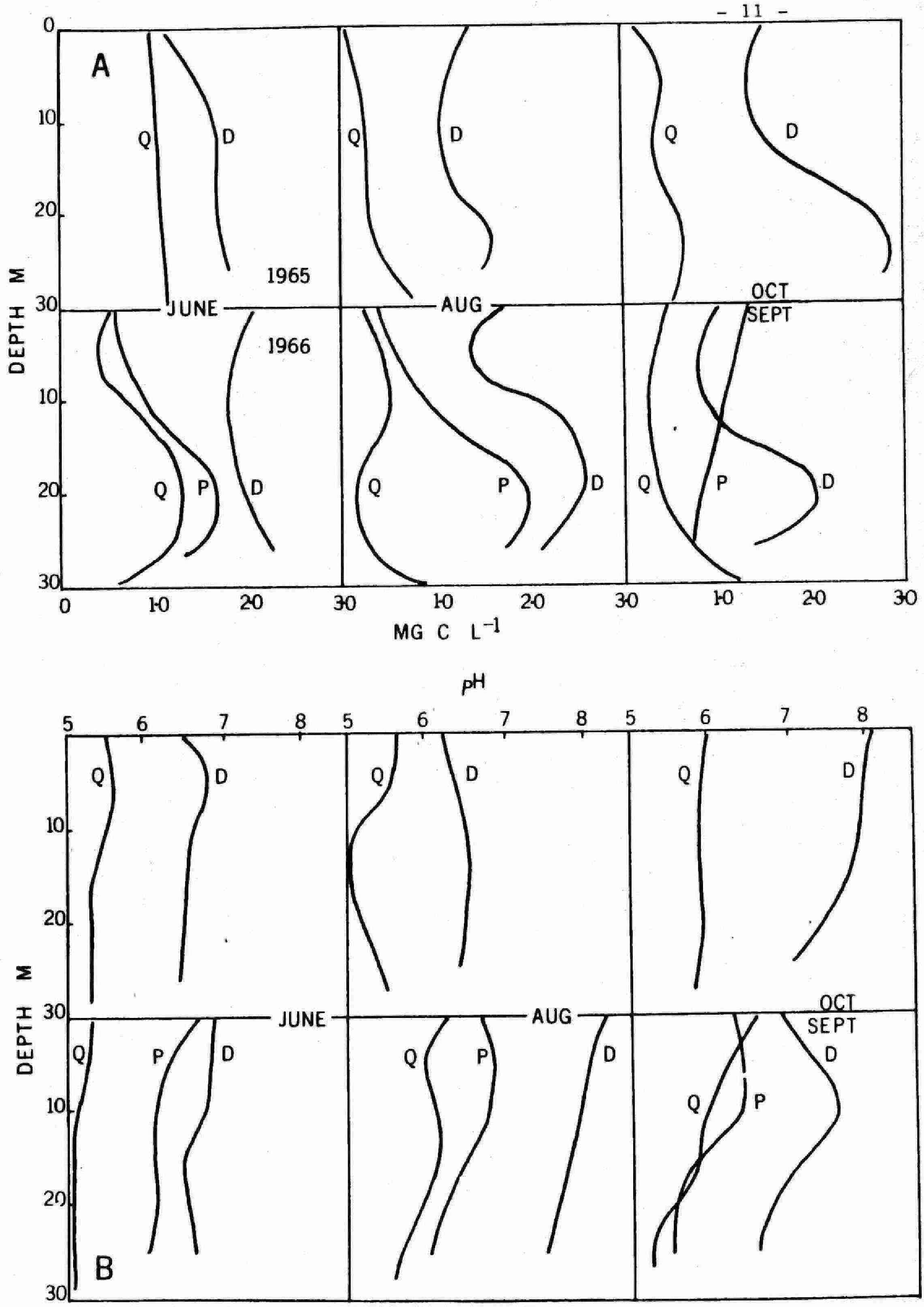


Figure 2 - Vertical variation in A. concentration of inorganic carbon and, B. pH, both determined at the times of measurement of primary productivity.

The pH of Quirke Lake was less at every depth and on every occasion than that of Dunlop Lake (Figure 2). Pecors Lake showed intermediate pH.

The apparent direct relationship between pH and total inorganic carbon in the epilimnion appears to be of considerable significance in this study and will be discussed further.

3.3 Phosphorus, nitrogen and silica

Levels of soluble and total phosphorus (Table 2) in the three lakes were similar, whereas nitrate and Kjeldahl nitrogen increased in order from Dunlop to Quirke to Pecors Lakes. Compared with Dunlop Lake, only slightly less orthosilicate was detected in Quirke and Pecors Lakes.

3.4 Light and temperature

The Secchi-disc transparency of lakes affected by mine wastes was generally greater than in unaffected lakes. Such was the case in comparing Dunlop (8 m) and Quirke (15 m) Lakes in August, 1965, although transparency was similar in June (10 m). In 1966, a photometer was available to provide additional evidence of similar transparency in Quirke and Dunlop Lakes in spring followed by progressively increasing transparency in Quirke Lake until, by late summer, it was almost twice that in Dunlop Lake (Figure 3).

The times of formation and disruption of the thermocline and its depth in the two lakes were similar (Figure 3).

The greatest difference in the two lakes, considering both optical and thermal characteristics, was in the position of the euphotic zone with respect to the thermocline (the depth of 1% incident light approximated the lower limit of the euphotic zone). The euphotic zone extended well into the hypolimnion in Quirke Lake but was confined to the epilimnion and thermocline in Dunlop Lake. Pecors Lake, for which less data are available, resembled Quirke Lake with the euphotic zone extending prominently into the hypolimnion.

TABLE II. Nutrient levels in Dunlop Lake and Quirke Lake, 1965 through 1967, and in Pecors Lake, 1966 and 1967. Values of phosphorus are expressed in mg PO_4 l^{-1}, total Kjeldahl nitrogen (including ammonia) and nitrate as mg N l^{-1}, and orthosilicate as mg SiO_2 l^{-1}

Nutrient	Dunlop Lake			Quirke Lake			Pecors Lake		
	Mean	Range	No. of Analyses	Mean	Range	No. of Analyses	Mean	Range	No. of Analyses
Soluble Phosphorus	0.03	0.00-0.21	58	0.03	0.00-0.32	64	0.05	0.00-0.28	46
Total Phosphorus	0.07	0.00-0.70	91	0.06	0.00-1.40	95	0.06	0.00-0.56	44
Nitrate	0.10	0.00-0.50	73	2.90	0.70-5.50	80	3.2	1.1 -7.5	48
Total Kjeldahl	0.69	0.07-2.50	43	1.80	1.00-8.30	87	2.36	0.26-9.90	57
Orthosilicate	0.89	0.22-2.10	41	0.54	0.24-0.90	22	0.58	0.28-0.79	14

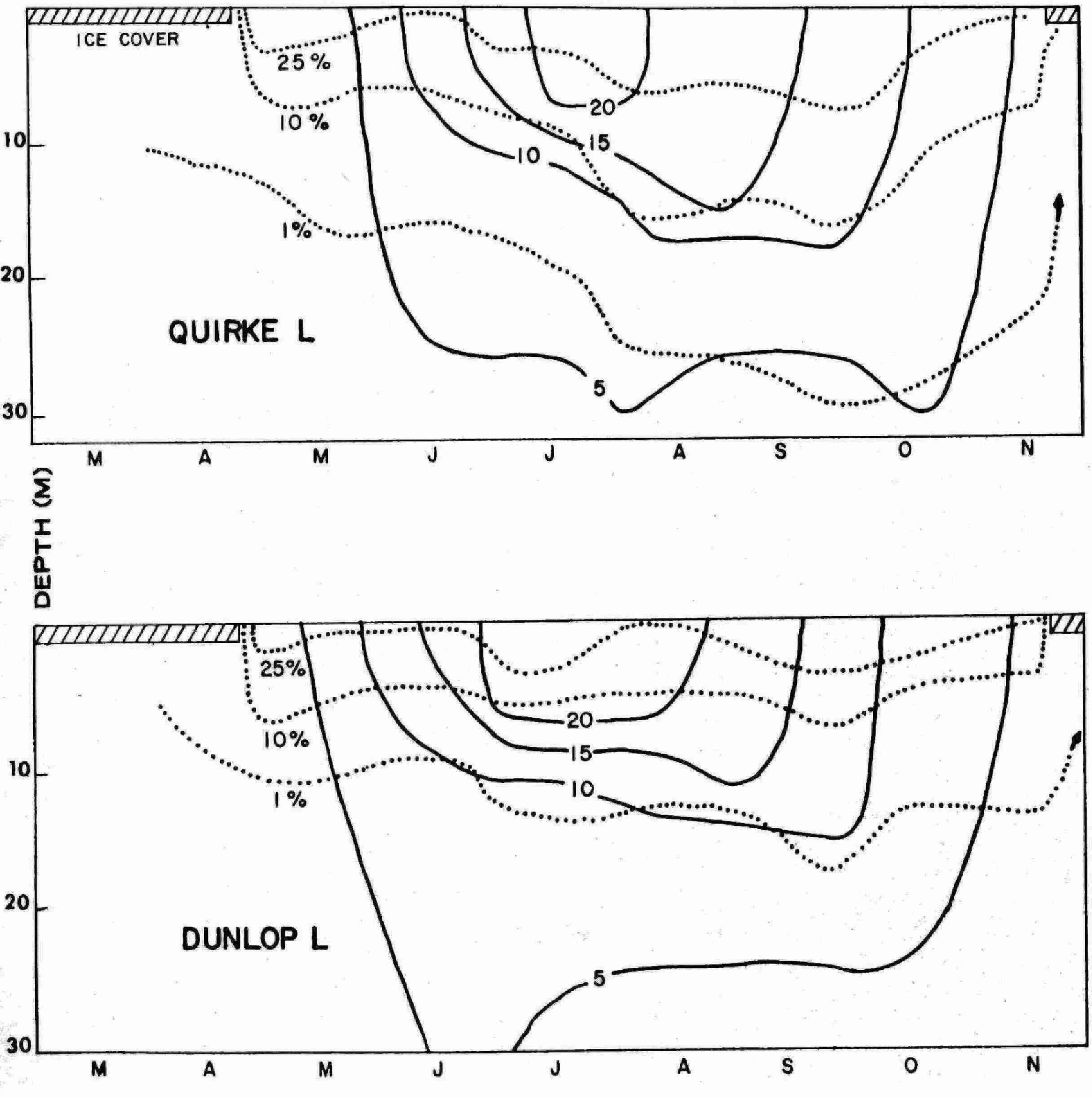


Figure 3 - Isotherms (solid lines) and isophots (dotted lines) in Quirke and Dunlop Lakes during the period of sampling in 1966.

4.0 SEASONAL AND VERTICAL DISTRIBUTION OF PHYTOPLANKTON

Definite changes in levels and composition of standing crops of phytoplankton were observed in the three lakes. Phytoplankton populations decreased in order from Dunlop to Quirke to Pecors Lakes. In 1966, average standing crops were 62, 30 and 21 organisms per ml in Dunlop, Quirke and Pecors Lakes, respectively. Corresponding values in 1967 were 206, 168 and 31 organisms per ml.

Changes in the specific composition of the phytoplankton were observed between the two contaminated lakes and the unaffected lake. The distribution by classes of the various algae reported from Dunlop, Quirke and Pecors Lakes during the study period are summarized (Table 3). Further examination of temporal and vertical changes in specific composition more adequately reflects the impact of acid mine wastes on phytoplankton communities.

4.1 Dunlop Lake

In Dunlop Lake the standing crop of phytoplankton was generally higher in 1967 than in 1966, largely due to increased numbers of Chrysophyceae, Myxophyceae and Bacillariophyceae. Although the 1967 sampling period was not as extensive as that of 1966, two major periods of phytoplankton development were evident in both years.

During the first peak period in the spring of 1966, the dominant alga, *Aphanizomenon flos-aquae* var. *gracile* was concentrated in the upper and intermediate depths of the lake. The highest average count (all depths) of 125 filaments per ml occurred on April 28 and the alga disappeared by the middle of May. As the sampling program for Dunlop Lake was not initiated until May 16 in 1967, there was no record of an early spring blue-green pulse. However, low numbers of *Aphanizomenon flos-aquae* var. *gracile* were found in the May 16 samples indicating that an earlier period of development may have existed.

TABLE III. Distribution of phytoplankton in Dunlop, Quirke and Pecors Lakes during the spring, summer and fall months, 1966 and 1967.

	Dunlop Lake	Quirke Lake	Pecors Lake
Bacillariophyceae			
Asterionella formosa Hassal	x	x	x
A. gracillima (Hantzsch) Heiberg		x	
Cocconeis sp.			x
Cyclotella bodanica Eulenstein	x	x	
C. glomerata Bachmann	x		x
C. ocellata Pantocsek	x		
Cymbella affinis Kützing			x
Diatoma vulgare Bory			x
Eunotia pectinalis var. *minor* (Kütz) (Rabenhorst)		x	x
Fragilaria crotonensis Kitton	x	x	x
Gomphonema sp.		x	
Melosira italica (Ehr.) Kützing	x	x	x
Navicula spp.	x	x	x
Nitzschia spp.	x	x	x
N. gracilis Hantzsch	x		
Pinnularia sp.		x	
Pleurosigma sp.			x
Surirella sp.	x		
S. angustata Kützing	x		
Synedra pulchella (Ralfs) Kützing	x	x	x
S. ulna (Nitzsch) Ehrenberg		x	
Tabellaria fenestrata (Lyngb.) Kützing	x	x	x
T. flocculosa (Roth) Kützing		x	x

Table III - cont'd

	Dunlop Lake	Quirke Lake	Pecors Lake
Chlorophyceae			
Actinastrum sp.		x	
Ankistrodesmus sp.	x	x	
A. falcatus (Corda) Ralfs			x
A. fractus (West and West) Brunnthaler			x
Arthrodesmus sp.	x	x	
A. triangularis var. *subtriangularis* (Borge) W. and G. S. West	x		
Carteria sp.		x	
Chlamydomonas spp.	x	x	x
Chlorella ellipsoidea Gerneck	x	x	x
C. vulgaris Beyerinck		x	
Closterium sp.		x	x
Coelastrum sp.		x	x
C. microporum Naegeli	x		
Cosmarium sp.	x	x	
Crucigenia quadrata Morren	x	x	
C. rectangularis (A. Braun) Gay	x	x	x
Dictyosphaerium sp.	x		
D. pulchellum Wood		x	
Euastrum sp.	x		
Gloeocystis gigas (Kützing) Lagerheim	x		
G. vesiculosa Naegeli	x		
Golenkinia radiata Chodat	x	x	
Kirchneriella sp.		x	
K. subsolitaria G. S. West	x		

Table III - cont'd

	Dunlop Lake	Quirke Lake	Pecors Lake
Micractinium pusillum Fresenius	x		
M. quadrisetum (Lemmermann) G. M. Smith	x		
Mougeotia sp.	x	x	x
Nephrocytium limneticum (G. M. Smith)	x		
Oedogonium sp.			x
Oocystis Borgei Snow	x		
O. parva West and G. S. West		x	
O. pusilla Hansgirg	x	x	x
Pediastrum Boryanum (Turpin) Meneghini	x		
Planktosphaeria gelatinosa G. M. Smith			x
Quadrigula closterioides (Bohlin) Printz	x		
Scenedesmus Bernardii G. M. Smith			x
S. biguga var. alternans (Reinsch) Hansgirg		x	
S. quadricauda (Turpin) Brebisson	x		
Schroederia sp.			x
Selenastrum minutum (Naeg.) Collins		x	x
Sphaerocystis schroeteri Chodat	x		x
Spirogyra sp.			x
Staurastrum sp.		x	x
S. Johnsonii West and G. S. West	x		
Tetraedron sp.		x	
T. minimum (A. Braun) Hansgirg			x
Ulothrix sp.	x	x	

Table III - Cont'd

	Dunlop Lake	Quirke Lake	Pecors Lake
Chrysophyceae			
Chrysophaerella longispina Lauterborn	x		
Dinobryon bavaricum Imhof	x		x
D. cylindricum Imhof	x	x	x
D. sertularia Ehrenberg	x	x	x
D. sociale Ehrenberg	x	x	x
D. sociale var. americanum (Brunn.) Bachmann	x	x	
D. Vanhoeffenii (Krieg.) Bachmann	x		
Mallomonas acaroides Perty	x		
Rhizochrysis limnetica G. M. Smith	x		
Synura uvella Ehrenberg	x		
Cryptophyceae			
Cryptomonas erosa Ehrenberg	x		x
C. ovata Ehrenberg	x		x
Dinophyceae			
Certium hirundinella (O.F. Muell) Dujardin	x		
Glenodinium quadridens (Stein) Schiller		x	
Peridinium cinctum (Muell.) Ehrenberg	x		x
P. inconspicuum Lemmermann		x	
P. pusillum (Penard) Lemmermann		x	x

Table III - Cont'd

	Dunlop Lake	Quirke Lake	Pecors Lake
Euglenophyceae			
Euglena sp.	x	x	x
Trachelomonas sp.		x	
T. robusta Swirenko		x	x
Myxophyceae			
Anabaena sp.			x
A. spiroides var. *crassa* Lemmermann	x		
Aphanizomenon flos-aquae var *gracile* (Lemmermann) Elenkin	x	x	x
Aphanocapsa elachista West and West	x		
A. elachista var. *conferta* West and West	x	x	
A. pulchra (Kützing) Rabenhorst	x		
Aphanothece clathrata G. S. West	x		
A. gelatinosa (Henn.) Lemmermann	x		
A. saxicola Naegeli	x		
Chroococcus dispersus (Keissler) Lemmermann	x	x	
C. limneticus Lemmermann	x		x
C. limneticus var. *carneus* (Chodat) Lemmermann	x		
C. Prescottii Drouet and Daily	x	x	x
C. turgidus (Kützing) Naegeli	x		
Coelosphaerium Kuetzingianum Naegeli	x		
C. Naegelianum Unger	x		

Table III - Cont'd

	Dunlop Lake	Quirke Lake	Pecors Lake
C. pallidum Lemmermann	x		
Dactylococcopsis acicularis Lemmermann	x	x	
D. fascicularis Lemmermann		x	x
D. rhaphidioides Hansgirg	x	x	x
D. Smithii Chodat and Chodat	x	x	x
Gloeothece rupestris (Lyngb.) Bornet	x	x	x
Gloeotrichia natans (Hedwig) Rabenhorst		x	
Gomphosphaeria spp.	x		
G. lacustris Chodat			x
Merismopedia convoluta Brebisson	x		
M. glauca (Ehrenberg) Naegeli	x		
M. tenuissima Lemmermann	x		
Oscillatoria subbrevis Schmidle		x	
Plectonema notatum Schmidle		x	x
Rhabdoderma Gorskii Woloszynska	x		
R. lineare Schmidle and Lauterborn	x	x	x
Xanthophyceae			
Botryococcus Braunii Kützing	x	x	x
B. protuberans W. and G. S. West	x		

In 1967, the first major pulse, extending from May to August, was characterized by high numbers of Chrysophyceae. Representatives of this class were also present in low to moderate numbers from May to July in 1966. In both years, the Chrysophyceae included *Dinobryon divergens*, *D. bavaricum*, *D. sociale*, *D. Vanhoeffenii*, *D. cylindricum* and *D. sertularia*. In addition to these species, moderate numbers of *Chrysophaerella longispina* were recorded from Dunlop Lake during May and June of 1967. Highest average counts of 30 and 269 cells per ml were recorded on May 17, 1966 and July 15, 1967, respectively. Highest numbers of Chrysophyceae were found at 10-14 m in both years. In 1966, the chrysophycean population gradually decreased so that by the end of July it was virtually absent. In contrast, the 1967 decline was abrupt, occurring near the end of August.

The second period of phytoplankton development materialized in both years during August and continued until the beginning of November in 1966 and until sampling was discontinued early in October of 1967. In contrast to the 1966 spring-time condition, when only one alga dominated, the mid-summer standing crops for both years were characterized by four species of *Chroococcus*, three species each of *Aphanothece*, *Dactylococcopsis*, *Coelosphaerium* and *Merismopedia*, two species each of *Aphanocapsa*, and *Rhabdoderma* and *Gomphosphaeria lacustris*. Greatest numbers occurred above the thermocline but no near-surface concentrations were observed. Maximum blue-green populations during these periods averaged 135 and 163 organisms per ml recorded on August 15, 1966 and August 30, 1967, respectively.

In both years the major diatoms included *Cyclotella bodanica*, *C. glomerata*, *Asterionella formosa*, *Tabellaria fenestrata* and *Melosira italica* and were found during the entire sampling period. In 1966, diatom averages varied between 7 (November 15) and 26 (August 3) cells per ml, but in 1967, corresponding values were higher, ranging between 20 (July 15) and 106 (July 28) cells per ml. For both years maximum numbers appeared in samples collected from 18-22 m. The Chlorophyceae, although present on every sampling occasion, never exceeded an average of 4 organisms per ml in 1966 and 20 organisms per ml in 1967, and were evenly distributed throughout the euphotic zone. Representatives of the

Cryptophyceae were not recorded from Dunlop Lake in 1966. In 1967, however, small numbers of Cryptomonas erosa were encountered in the euphotic zone.

4.2 Quirke Lake

The standing crop of phytoplankton increased from 1966 to 1967 due entirely to dominance of a single blue-green species. Two periods of phytoplankton development occurred in 1966 and one in 1967.

In 1966, the first and larger pulse was recorded during April when Aphanizomenon flos-aquae var. gracile dominated and was found in highest numbers at 7-22 m. The highest average for this alga of 73 organisms per ml was somewhat lower than that recorded for the same period in Dunlop Lake. A gradual decline in numbers of Aphanizomenon flos-aquae continued until the end of May. As sampling did not commence until May 15 of 1967 in Quirke Lake, it is impossible to confirm whether a blue-green pulse of Aphanizomenon flos-aquae had developed earlier in the year.

In both years phytoplankton levels increased rapidly commencing in the first week of June. During these peak periods of production, the standing crops were dominated almost entirely by the blue-green form Plectonema notatum, which appeared evenly distributed vertically to the maximum depth sampled. Although Plectonema declined gradually until mid-November in 1966, in 1967 numbers of this species prevailed until the sampling program was curtailed in the first week of October.

With minor exception (i.e. small numbers of Dinobryon sertularia, D. cyclindricum and D. sociale in June and August of 1966 and September and October of 1967), representatives of the Chrysophyceae and Bacillariophyceae were rarely encountered in Quirke Lake during the study. Chlorophycean algae occurred consistently in Quirke Lake attaining maximum averages of 16 organisms per ml on July 13, 1966 and 37 organisms per ml on July 14, 1967. Although absent in 1966, Peridinium pusillum, a dinoflagellate, was found regularly in the 1967 samples. Cryptophycean algae were not observed in any of the samples collected.

4.3 Pecors Lake

As regular samples were not collected from Pecors Lake in 1966, it was impossible to determine accurately changes in the qualitative and quantitative seasonal and vertical distribution of phytoplankton communities. However, regular sampling was carried out during the summer of 1967.

On June 14, 1966, a number of species of *Dinobryon*, including *D. bavaricum*, *D. cylindricum*, *D. sertularia* and *D. sociale* averaged 39 organisms per ml. These algae dominated at all depths, but were found in greatest numbers in the samples collected from the lower euphotic zone. Although the same species were encountered throughout the entire period in 1967, corresponding numbers were extremely low, ranging between 2 organisms per ml on June 6 and 7 organisms per ml on June 28.

On August 17 and September 28 (the only other days when samples were collected in 1966), the major alga, *Plectonema notatum*, attained average maxima of 8 and 9 organisms per ml, respectively.

In 1967, the main period of phytoplankton development occurred between August 2 and the end of September. During that time, *Chlamydomonas* spp. and *Plectonema* were the dominant algae with maximum averages of 23 and 18 organisms per ml, respectively. Optimum conditions for these algae appeared limited to the intermediate depths (10-18 m) of the lake. Although chlorophcean algae were encountered on each of the three sampling dates in 1966, their numbers were extremely low, never exceeding a mean of 4 organisms per ml, which occurred on September 28. These algae were rarely encountered in 1967.

Generally, the diatoms were absent during the study period. However, representatives of this class were present in July and August of 1967 when levels of 5-10 organisms per ml were recorded. The major species, *Synedra ulna*, *S. pulchella* and *Tabellaria fenestrata* were evenly distributed throughout the water column to a depth of 22 m. Low numbers of *Peridinium pusillum* and *Cryptomonas erosa* were recorded in 1967 but were not observed in 1966.

4.4 Species diversity

Table 4 summarizes the mean, maximum and minimum indices of diversity for each sampling date in the three lakes. With one exception (May 16, 1967) mean indices of diversity in Quirke and Pecors Lakes were lower than those in Dunlop Lake. A trend toward increased diversity during the later summer and fall months in the three lakes was observed. The index of diversity within the three communities was usually inversely related to standing crops of phytoplankton. For example, in March and April 1966, the phytoplankton communities in Quirke and Dunlop Lakes were dominated by high numbers of *Aphanizomenon flos-aquae* var. *gracile*. During this period, indices of diversity were relatively low at 2.74 and 3.02 in Dunlop Lake and 1.66 and 1.53 in Quirke Lake. One exception occurred in Dunlop Lake in summer when both the standing crops and indices of diversity were high.

TABLE IV. Mean, minimum and maximum values of the Index of Diversity (I) for each sampling date in Dunlop, Quirke and Pecors Lakes, 1966-1967. Arithmetic mean I is based on 5-6 samples collected from a series of depths on each date.

Date	Dunlop Lake			Quirke Lake			Pecors Lake		
	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum
1966									
March 31	2.74	1.60	4.10	1.66	0.81	2.53			
April 29	3.02	2.43	3.63	1.53	0.99	2.03			
May 19	3.59	2.60	4.36	4.85	0.73	5.87			
June 14	4.50	3.09	6.66	1.10	0.56	1.54			
June 28	5.99	4.67	7.69	1.63	0.84	3.41			
June 29							2.87	1.91	3.71
July 13	6.91	5.06	8.93	1.81	1.17	2.83			
July 28	4.94	3.50	5.88	3.21	1.12	6.49			
August 13	6.68	4.79	7.79	2.30	0.99	4.05			
August 17							2.89	1.69	3.94
August 30				2.43	1.60	3.14			
September 26	6.74	5.33	7.79	2.11	0.52	5.07			
September 28							3.66	2.69	4.93
October 20	7.53	5.93	9.27	5.12	3.17	6.31			
November 15	9.59	7.40	11.59	6.91	4.68	8.04			
1967									
May 16 & 17	3.61	2.22	4.79	3.81	3.33	4.31	3.60	3.46	4.01
June 6 & 7	4.57	2.43	8.04	2.89	2.00	3.93	2.80	2.32	4.00
June 27 & 28	5.88	4.65	7.30	3.30	2.65	3.98	3.80	2.15	4.90
July 13,14 & 15	6.57	4.42	8.88	3.37	2.41	4.48	3.10	2.53	4.46
July 27 & 28	9.02	6.50	12.25	2.34	0.68	4.83	4.00	0.91	7.63
August 28 & 31	7.09	5.07	9.41	4.03	1.77	5.47	3.80	3.21	5.00
September 13	7.81	5.14	9.71	4.25	3.26	5.64			
October 2 & 3	8.22	7.52	9.20	4.09	2.79	5.48	3.30	2.07	4.69

5.0 PRIMARY PRODUCTIVITY

5.1 Productivity per unit volume

Hourly rates of carbon assimilation (Appendix A: Tables 1 and 2) were as great as 2-3 mg C m^{-3} in Dunlop Lake during the development of blue-green algae in 1966. Rates exceeding 1 mg C m^{-3} hr^{-1} were common in Dunlop Lake and rare in Quirke Lake, while the maximum rate observed in Pecors Lake was 0.4 mg C m^{-3} hr^{-1}. Although integrals (mg C m^{-2} hr^{-1}) should be used when comparing productivities of the lakes, an examination of volume-based rates with corresponding concentrations of nutrients, light intensity and standing crops of algae is informative. Inorganic carbon appeared to be the most important of the nutrients in controlling productivity. This variable, together with data on light and algal standing crops, were related in multiple regression to primary productivity. The multiple correlation coefficient was 0.70 while the simple correlation coefficients were 0.52 for algal crop, 0.36 for inorganic carbon and 0.32 for light intensity. The estimating equation is: $PP = -0.9065 + 0.0045A + 0.2701C + 1.4007 \log I$ where PP is primary productivity in mg C m^{-3} hr^{-1}, A is algal standing crop in areal standard units per ml, C is inorganic carbon in mg C l^{-1} and I is light intensity in lux.

5.2 Areal productivity

Integrals of hourly primary productivity are presented graphically with areal standing crops of algae, transparency and position of the thermocline (Figure 4). Means of primary productivity measurements in Dunlop, Quirke and Pecors Lakes were 12.6, 7.0 and 3.3 mg C m^{-2} hr^{-1}, respectively. Extrapolation to mean daily rates gives 126, 71 and 34 mg C m^{-2}.

All of the lakes should be classified as oligotrophic on the basis of absolute levels of primary productivity. (See Table 10 in Wetzel, 1964 and Table 9 in Strickland, 1960 for comparison of many fresh and marine water bodies). However, indications of mesotrophy in Dunlop Lake are the clinograde oxygen distribution in summer, the presence of many species of blue-green algae in rather large numbers in mid-summer,

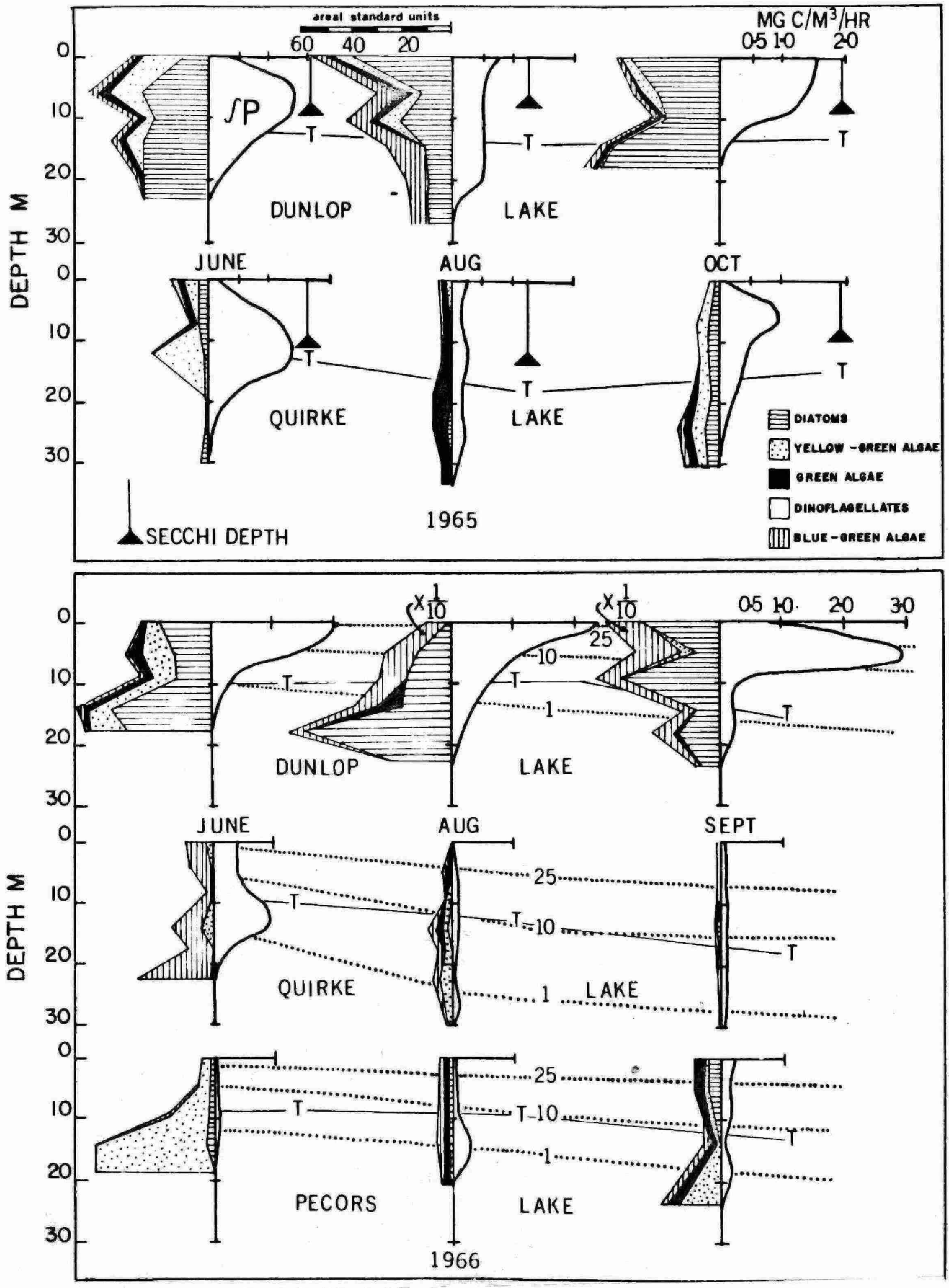


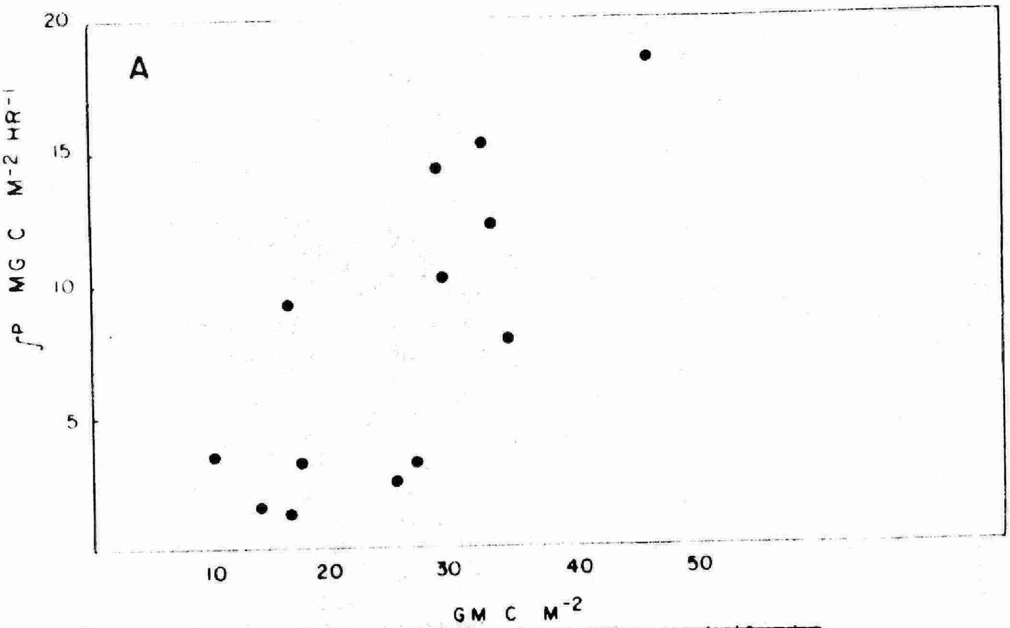
Figure 4 - Vertical variation in carbon assimilation (mg C m^3 hr^{-1}) and standing crops of algae (asu) by taxonomic classes. Isophots (dotted lines) and the general position of the thermocline are shown.

particularly in 1967. The vertical distribution of photosynthesis with near-surface maximum and decrease with depth corresponding to the exponential decrease in light (Figure 4) was characteristic of Dunlop Lake except in August, 1965. The common distribution resembled Findenegg's Type I (1964) of eutrophic lakes. Findenegg considered that ".... the shape of the vertical assimilation curve is very much more informative with regard to the degree of eutrophication than is the amount of organic matter produced per surface unit". His Type II, characteristic of oligotrophic lakes, has an orthograde distribution of assimilation with light inhibition in the uppermost layer and no depth of pronounced optimal photosynthesis through a deep euphotic zone. The scarcity of nutrients rather than decreasing light limits photosynthesis. Quirke Lake showed this type on several occasions, although in June, 1965, vertical assimilation was obviously of Type I and assimilation approached Type I in October, 1965 and June, 1966. Pecors Lake had the Type II curve but showed above-average assimilation in the hypolimnion at very low light intensity (1% of incident light), as did Quirke Lake each mid-summer. The greater concentration of inorganic carbon and perhaps other nutrients and growth factors in the hypolimnion appeared to be responsible.

The 15 areal estimates of productivity were related to the corresponding amounts of inorganic carbon and algae in the euphotic zone (Figure 5). In multiple regression analysis 63% of the variability in primary productivity was accounted for by variations in standing crop of algae and concentrations of inorganic carbon. The estimating equation is: $PP = -10.5495 + 2.3813 \log A + 0.1996\ C$ where PP is in mg C m^{-2} hr^{-1}, A is asu m^{-2} / 10^9 of phytoplankton and C is inorganic carbon in mg C m^{-2}.

5.3 Bioassays

The increase of inorganic carbon by 6 mg C l^{-1} in Quirke Lake doubled the rate of primary productivity in the experimental bags (Table 5). The addition of phosphate did not produce an increase. Both phosphate and inorganic carbon alone increased productivity in polyethylene bags in Dunlop Lake, while the combination provided the greatest increase over productivity in control bags. Although this bioassay



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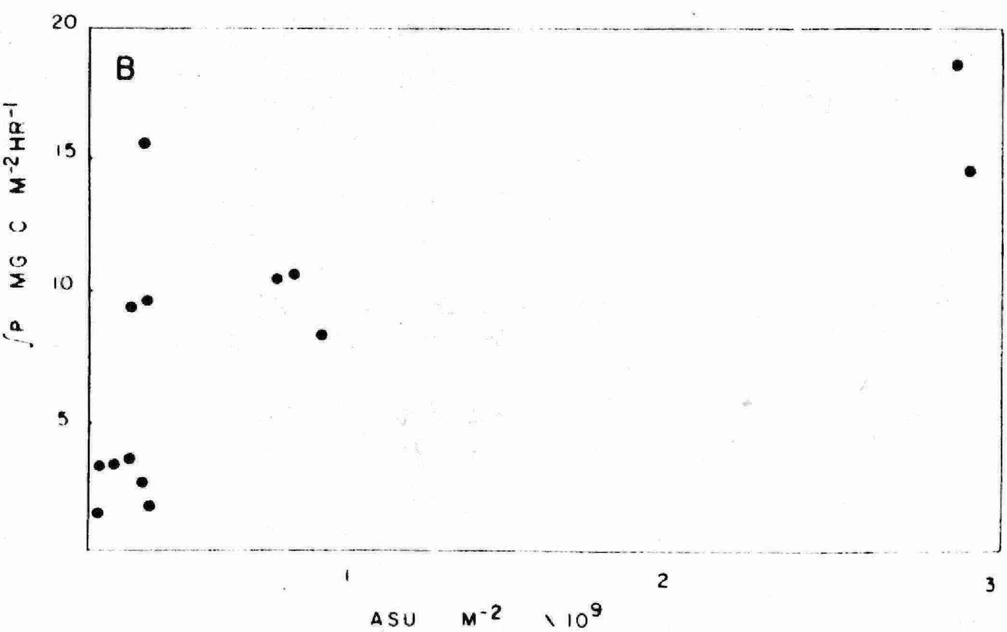

Figure 5 - Relationships between integrals of primary productivity and A. inorganic carbon in the euphotic zone, and B. algal standing crop in the euphotic zone. Regression analyses considering both carbon and algae are discussed in the text.

TABLE V. Carbon assimilation (mg C m^{-3} hr^{-1}) in Quirke and Dunlop lake waters in plastic bags with and without nutrient additions as indicated.

Addition	Quirke Lake	Dunlop Lake
None	0.13	0.38
	0.08	0.93
Phosphate (0.2 mg PO_4 l^{-1})	0.19	1.11
	0.13	1.21
Inorganic carbon (6 mg C l^{-1})	0.24	1.88
	0.23	1.45
Inorganic carbon and phosphate	0.27	3.73
	0.25	4.00

experiment was carried out only once, it pointed to the importance of inorganic carbon in epilimnetic waters, at least in mid-summer in both Quirke and Dunlop Lakes. The lack of response to phosphate in Quirke Lake may have occurred because of the greater limiting role of inorganic carbon or preference of the phytoplankton species present at the time (e.g. Dinobryon spp.) for low concentrations of phosphate.

The laboratory experiment showed increasing assimilation with increasing inorganic carbon concentrations whether phosphate had been added or not. Assimilation appeared to reach an asymptotic level of 0.7-1.0 mg C m^{-3} hr^{-1} at about 5 mg C l^{-1} in both lake waters (Figure 6). The interaction of phosphate and carbon did not give maximum assimilation in Dunlop water in the laboratory as it had done in the field.

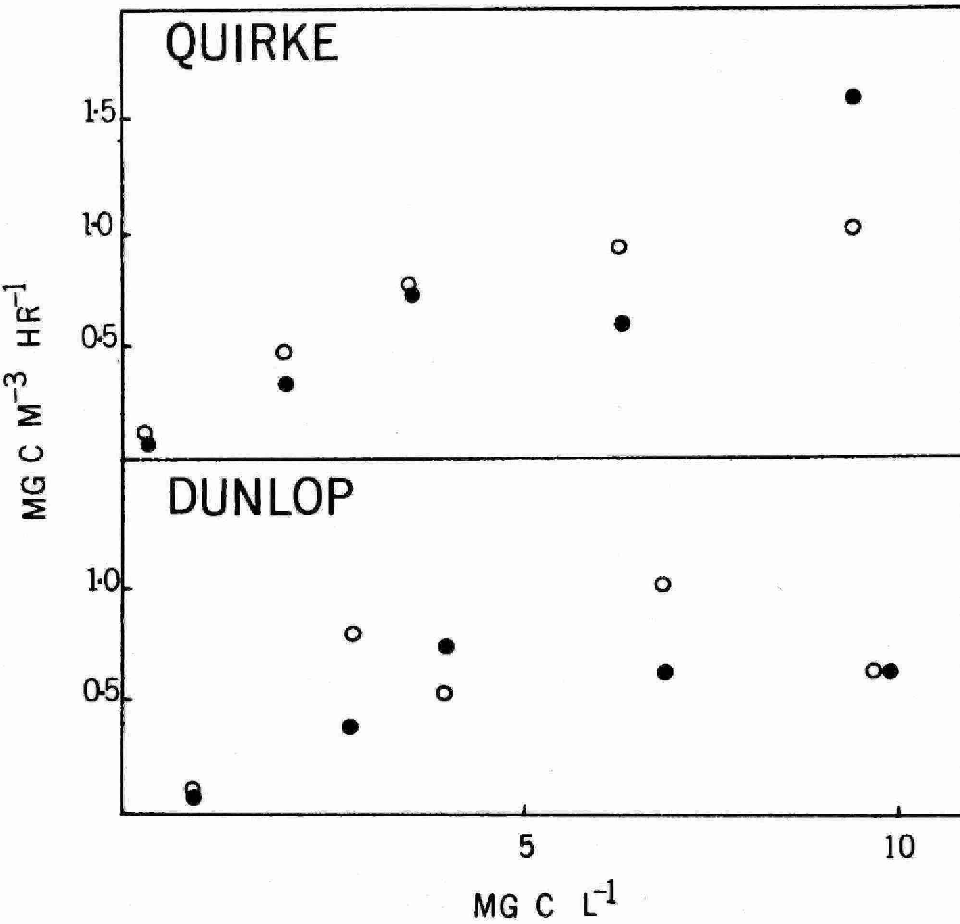

Figure 6 - Relationship between carbon assimilation and concentration of inorganic carbon following additions of $NaHCO_3$ in *in vitro* bioassays. Phosphorus (0.2 mg PO_4 l^{-1}) was added to one half of the samples (closed circles).

6.0 EFFECTS OF ACID MINE WASTES

6.1 Changes in lake chemistry

Differences in the chemical composition of lakes affected by acid mine wastes can be related to various processes used in the extraction of uranium and subsequent treatment of wastes. For example, sulphuric acid is used in leaching milled ore, nitric acid in eluting uranium from ion-exchange resins and lime in neutralizing "barren" solution. These processes account for the increased concentrations of SO_4^{-2}, NO_3^{-1} and Ca^{+2}.

Acid wastewater is now neutralized with CaO prior to impoundment in the tailings areas, although this was not done in the earliest operations. However, effluents from the ponds to the main lakes have a low pH, probably due to bacterial oxidation of metallic sulphides in the tailings, and provide the high free mineral acidity characteristic of contaminated lakes (Table 1).

Low concentrations of inorganic carbon are associated with low pH (Figure 2). The low inorganic carbon results from the reduced solubility of CO_2 and its loss from the epilimnion stirred by wave action and possibly by reduced regeneration of CO_2 from the sediments.

Other nutrients were in greater supply in the contaminated lakes than in the reference lake (e.g. nitrate), or occurred in concentrations similar to the reference lake (e.g. phosphorus and silica). Heavy metals did not appear to have attained high concentrations in contaminated lakes.

6.2 Comparison of species composition

Several notable differences were observed in the species composition of phytoplankton between the reference and contaminated lakes. Firstly, many species of the Bacillariophyceae, Chrysophyceae and Myxophyceae developed in Dunlop Lake but were absent or occurred in extremely low numbers in Quirke and Pecors Lakes. Secondly, several species were found regularly only in contaminated lakes including the

diatom Eunotia pectinalis var. minor, which tolerates high calcium concentrations and develops especially well in acid waters (Patrick and Reimer 1966), and the blue-gree alga Plectonema notatum, which may be confined to waters of low pH. Three members of the Chroococcales (Myxophyceae), Chroococcus Prescottii, Dactylococcopsis Smithii and Rhabdoderma lineare, were found in greater numbers in the contaminated lakes than in Dunlop Lake. Apparently, these species tend to flourish in acid waters (Prescott 1951).

Similarities in species composition occurred, shown particularly by the importance of Aphanizomenon flos-aquae var. gracile in the three lakes, but the communities of these lakes clearly had individual characteristics. Modification of communities in adapting to conditions of high salts and low pH was apparent in the resemblance of the communities in Quirke and Pecors Lakes which otherwise are least alike (e.g. size and depth).

6.3 Species diversity

Average species diversity throughout the sampling periods was proportional to average population size in the three lakes. Therefore, the reduction in the population of phytoplankton in contaminated lakes appears to be due to the elimination of species as well as to reduction in numbers of surviving species. However, when higher numbers were attained in contaminated lakes, diversity did not increase. For example, the numbers of phytoplankton were relatively high in Quirke Lake in July in both 1966 and 1967, but species diversity was low because Plectonema notatum dominated. In contrast, several species comprised the large population which developed in Dunlop Lake each summer. A greater degree of community organization is indicated in the reference lake, while modification of the environment in contaminated lakes appears to lead to lower organization and to the general occurrence of opportunistic species like Plectonema notatum. The development of an opportunistic species Aphanizomenon flos-aquae var. gracile, in the reference lake, concurrent with low species diversity, was confined to the initial spring pulse.

The cyclical seasonal trend in species diversity, low in the spring with a general increase toward fall (Table 4) is a transition which might be of general occurrence in these lakes. Although this cycle is of interest from the viewpoint of ecosystem succession, maturity and organization, we have not pursued the matter in the present study.

6.4 Abundance and distribution of phytoplankton

Contaminated lakes had low populations of phytoplankton. Average numbers per ml throughout the study were 134 in Dunlop, the reference lake, and 99 and 25 in Quirke and Pecors Lakes, respectively.

Maximum numbers in Dunlop Lake occurred higher in the euphotic zone than in Quirke and Pecors Lakes where the phytoplankton was either rather evenly distributed throughout the euphotic zone or confined to the lower portion within the thermocline and in the hypolimnion. The latter distribution provides some evidence of more favourable conditions in the lower euphotic zone in contaminated lakes, which is where greater concentrations of inorganic carbon are available.

The seasonal distribution of phytoplankton was similar in all lakes, with two periods of development as described previously.

6.5 Primary productivity

The importance of inorganic carbon in limiting primary productivity was apparent in *in situ* areal and volumetric measurements, in laboratory bioassays and in bioassays carried out in polyethylene bags in the lakes. Although levels of phosphorus were similar in the three lakes, added phosphate increased carbon assimilation in polyethylene bags only in the reference lake (Table 5). Although all evidence obtained to date points to the limiting role of inorganic carbon in contaminated lakes, the importance of other factors should not be discounted (e.g. ratio of monovalent and divalent ions and changes in concentrations of dissolved organic substances including growth factors).

Average primary productivity in Dunlop, Quirke and Pecors Lakes was 126, 71 and 34 mg m^{-2} day^{-1}, respectively. Generally, Dunlop Lake was more productive than the contaminated lakes. However, Quirke Lake had rates similar to those in Dunlop on three occasions (Figure 4). On these occasions the flow from Dunlop to Quirke was high. Possibly the inflow of water richer in inorganic carbon maintained a higher primary productivity in Quirke Lake. Pecors Lake, which is supplied by water generally low in inorganic carbon, was characterized by low standing crops of phytoplankton and low productivity throughout the study.

A compensatory mechanism acts to reduce but does not eliminate the loss of inorganic carbon from contaminated lakes. The reduction in phytoplankton, among other possible factors, led to an increase in the depth of the euphotic zone, which extended into the hypolimnion in Quirke and Pecors Lakes (Figure 3). The average standing crop of phytoplankton in Dunlop Lake at times when productivity was measured was 68 asu. In Pecors and Quirke Lakes crops were 7 and 18 asu, 10 and 24% of the phytoplankton in Dunlop Lake. The average depth of the euphotic zone in Pecors and Quirke Lakes at these times was 110 and 130% of that in Dunlop Lake where it was 22 m. Therefore, any compensating effect of lower concentrations of phytoplankton in producing a deeper euphotic zone appears to be of limited significance. However, an extension of the euphotic zone into the hypolimnion, where greater concentrations of inorganic carbon occurred (Figure 2), might be expected to enhance this mechanism if sufficient light remained. The depth of overlap of the hypolimnion and euphotic zone received 1-10% of incident light and a large proportion of the total carbon was assimilated at a very low ($\pm$ 1%) light intensity in contaminated lakes (Figure 4). However, because the light was so reduced in the hypolimnion, the mechanisms described above fell far short of compensating for the reduction in species diversity and abundance of the phytoplankton which developed. Nonetheless, the most efficient use of inorganic carbon in contaminated lakes probably was the use of carbon held in the hypolimnion, much of which might otherwise have been lost from the lakes at times of complete circulation.

7.0 CONCLUSION

It is concluded that inorganic carbon limited primary productivity in the lakes contamined by acid mine wastes, with the reduced pH and inorganic carbon decreasing both the number of species and the total number of phytoplankton. Regeneration of inorganic carbon probably is impeded by acid conditions in these lakes and carbon is cycled inefficiently, much being lost at overturn and from the epilimnion during stratification. Outside sources of inorganic carbon appear to be of extra importance to contaminated lakes. The reduction in primary productivity in lakes affected by acid mine wastes would be expected to affect adversely higher trophic levels including fish and delay the removal of radionuclides to the deep sediments of the lakes.

8.0 RECOMMENDATIONS

1. Complete and continuous control of pH should be one of the primary objectives of acid mine waste treatment. Liquid wastes should be adequately treated and solids carefully controlled so as not to cause a decrease in the pH of receiving lakes below an OWRC approved point of control at the time of discharge and at any future time.

2. The feasibility of accelerating the reclamation of lakes already damaged by acid mine wastes should be investigated. The controlled addition of alkali and/or well buffered organic materials might be of practical value.

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APPENDIX A

APPENDIX A

Table 1. Duplicate measurements of carbon assimilation at selected depths (mg C m^{-3} hr^{-1}) and integrals of assimilation (mg C m^{-2} hr^{-1}) in Quirke and Dunlop Lakes on six dates in 1965 and 1966.

Depth(m)	1965 June 17	1965 Aug.10	1965 Oct.2	1966 June 14	1966 Aug. 3	1966 Sept. 26.
			Quirke Lake			
1	0.30	0.19	0.12	0.52	0.04	0.04
	0.26	-	0.19	0.23	0.02	0.03
7	0.92	-	0.80	0.54	0.05	0.05
	1.16	0.08	1.03	0.22	0.09	0.02
13	1.13	0.12	0.39	1.08	0.09	0.06
	1.46	0.27	0.27	0.58	0.08	0.18
19	0.26	0.04	0.19	0.24	-	0.06
	0.29	0.08	0.28	0.22	0.06	0.06
24	-	0.12	0.07	0.02	0.01	0.05
	0.09	0.04	0.05	0.02	0.01	0.04
30	0.04	0.06	0.02	< 0.01	0.05	0.03
	0.01	0.12	0.02	< 0.01	0.06	0.03
1-30	17.5	3.0	8.6	12.3	1.5	1.4
	14.0	4.1	11.0	7.0	1.9	1.7
			Dunlop Lake			
1	0.86	0.71	1.26	1.99	2.61	0.98
	-	0.54	1.50	1.97	2.10	0.73
6	1.05	0.47	1.05	1.11	2.22	3.60
	1.33	0.45	1.46	1.00	0.53	2.41
10	0.76	0.72	0.20	0.26	0.38	0.16
	0.85	0.72	0.25	0.19	0.56	-
14	0.32	0.18	0.03	0.10	0.31	0.17
	-	0.18	0.03	0.05	0.44	-
19	0.01	0.08	0.01	0.03	-	0.18
	< 0.01	0.06	0.01	0.01	-	0.26
23	< 0.01	0.02	< 0.01	< 0.01	< 0.01	0.02
	< 0.01	0.02	< 0.01	< 0.01	< 0.01	0.02
0-23	11.8	8.3	9.3	11.4	20.0	18.2
	14.0	7.9	11.9	9.6	17.9	11.3

APPENDIX A

Table 2. Duplicate measurements of carbon assimilation at selected depths (mg C m^{-3} hr^{-1}) and the two independent integrals of assimilation (mg C m^{-2} hr^{-1}) in Pecors Lake on three dates in 1966.

Depth (m)	June 29	August 17	September 28
1	0.04	0.04	0.25
	0.02	0.05	0.22
6	0.02	0.04	0.19
	0.06	0.18	0.17
10	0.06	0.07	0.15
	0.07	0.10	0.17
14	0.03	0.39	0.06
	0.10	0.29	0.06
19	0.02	0.15	0.13
	0.02	0.27	-
23	< 0.01	0.07	< 0.01
	< 0.01	0.07	< 0.01
0 - 23	1.1	3.2	3.1
	5.8	4.0	2.4

APPENDIX B

APPENDIX B

Table 1. Summary of data on phytoplankton collected in Dunlop Lake on three dates in 1965. Samples were collected at eight depths to 31 metres. Results are expressed in areal standard units per millilitre. (p indicates presence at <1 asu

	June 17								August 10								October 2							
	1	5	10	14	18	22	27	31	1	5	10	14	18	22	27	31	1	5	10	14	18	22	27	31
Myxophyceae																								
Gomphosphaeria	1	2	1						3	5	9	4	3	4	4	1	1	2	1	1	3	4	2	1
Anacystis	1	1	2	2	2				2	2	6	3	1	2	3	1	1	1	1	2	1	5	2	1
Aphanocapsa	p																							
Sub-total	2	3	3	2	2	p			5	7	15	7	4	6	7	2	2	3	2	3	4	9	4	2
Chrysophyceae																								
Dinobryon	16	13	3	8	1				9	3	9						4	6		p	1			
Mallomonas					p																			
Synura												p												
Sub-total	16	13	3	8	1				9	3	9	p					4	6		p	1			
Bacillariophyceae																								
Synedra	2	2	3	2	12	1	1		p		p		p	p		p	p	p		p				p
Melosira			1	2	5	11	13			1	p	2	p	2	p			1	1	1	2	3	1	2
Cyclotella	5	7	3	2	2	1	p		1		1	1	p	p	1		p	p	p		p	p		p
Asterionella	4	5	7	9	3	5	p		11	5	4	4	6	5	4	2	2	2	2	3	7	7	10	6
Navicula	1		1	p	1	1																		
Tabellaria		12	6	10	2	5	5		28	7	9	6	3	4	4	2	32	22	17	39	38	36	13	3
Pinnularia				p																				
Fragilaria									1												1	p	p	
Sub-total	12	26	21	25	25	24	19		41	13	14	13	9	11	9	4	34	25	20	43	47	46	24	11

Table 1. continued........

	June 17								August 10								October 2							
	1	5	10	14	18	22	27	31	1	5	10	14	18	22	27	31	1	5	10	14	18	22	27	31
Chlorophyceae																								
Dictyosphaerium	1																							
Scenedesmus	p		p			p	p													p	p		p	
Micractinium	p	p	1						1	1	1		p		p	p			1	1				
Chlorella		1	p																					
Quadrigula			1	p																				
Franceia			1																					
Crucigenia		p	p																					
Oocystis		2		p	p	p																		
Ankistrodesmus		p		p					p	p	p							p						
Gloeocystis				p																				
Euastrum			2																					
Chlamydomonas	1	1	p	1	1	1	p																	
Arthrodesmus		1		1	p				p	p		p	p						1	1	p			
Staurastrum									1	5	2	1	p			p		1	1			1		p
Micrasterias										p											p			
Closterium									p															
Sub-total	2	5	5	2	1	1	p		2	6	3	1	p		p	p		1	3	2	p	1	p	p
Euglenophyceae																								
Euglena	1		1																					
Sub-total	1		1																					
Dinophyceae																								
Peridinium	1	p		p			p						p											
Ceratium										1														
Sub-total	1	p		p			p			1			p											
TOTAL	34	47	33	37	29	25	19		57	30	41	21	13	17	16	6	40	35	25	48	52	56	28	13

APPENDIX B

Table 2. Summary of data on phytoplankton collected in Quirke Lake on three dates in 1965. Samples were collected at eight depths to 39 metres. Results are expressed in areal standard units per millilitre.

	June 17								August 10								October 2							
	1	6	12	17	23	28	34	39	1	6	12	17	23	28	34	39	1	6	12	17	23	28	34	39
Myxophyceae																								
Anabaena	p																							
Oscillatoria										1		p	p	p	p						1	1	p	2
Anacystis																						1		3
Sub-total	p									1		p	p	p	p						1	2	p	5
Chrysophyceae																								
Dinobryon	p	1	21	p		p	p	p	2	p	p			1			3	5	3	6	5	3	3	
Sub-total	p	1	21	p		p	p	p	2	p	p			1			3	5	3	6	5	3	3	
Bacillariophyceae																								
Synedra	1	1	p	p	p	p				p								1						
Melosira	1												1				1	4	2	3	6	2	1	19
Cyclotella	p	2	p	p		1																		
Asterionella		p					p																	
Navicula						1																		
Tabellaria																	1		1					
Fragilaria						p																		
Sub-total	2	3	p	p	p	2	p			p			1				2	5	3	3	6	2	1	19

Table 2. continued......

	June 17								August 10								October 2							
	1	6	12	17	23	28	34	39	1	6	12	17	23	28	34	39	1	6	12	17	23	28	34	39
Chlorophyceae																								
Chlorosarcina	p																							
Schroederia	p																							
Arthrodesmus	p		p																					
Mougeotia	1											4	5	3	3	2								
Ulothrix		1																			1	p	p	p
Scenedesmus				p		p						1		p									p	p
Actinastrum			p																					
Ankistrodesmus									1	2		p							p	p	p	1	p	
Chlorella											p	1	p	p	p	p				p	p	p	p	p
Closterium												p	p								1	1	p	1
Chlamydomonas		p	1	p	p	p			1	p	1	2	1	1	1	1				2	1	1	1	2
Sub-total	1	1	1	p	p	p			2	2	1	8	6	4	4	3			p	2	3	3	1	3
Euglenophyceae																								
Trachelomonas									1	p														
Sub-total									1	p														
Dinophyceae																								
Peridinium	1	p							1	1	1	p										p		
Sub-total	1	p							1	1	1	p										p		
TOTAL	4	5	22	p	p	2	p	p	6	4	2	8	7	5	4	3	5	10	6	11	15	10	5	27

APPENDIX B

Table 3. Summary of data on phytoplankton collected in Dunlop Lake on three dates in 1966. Samples were collected at six depths to 23 metres. Results are expressed in areal standard units per millilitre.

	June 14						August 3						September 26					
	1	5	10	14	18	22	1	5	10	14	18	22	1	5	10	14	18	22
Myxophyceae																		
Gomphosphaeria							14	9	5	13	6	2	14			5	16	4
Anacystis			p	p			73	116	94	70	60	8	119	156	108	53	52	24
Agmenellum							6	7	7	1	1	2	38	17	4	1	15	6
Coelosphaerium		1	p	p														
Chrococcus				p														
Anabaena										3				13	1			
Dactylococcopsis							1	3	3	1					1	2	2	p
Lyngbya							1		1									
Oscillatoria											2							
Sub-total		1	p	p			95	134	110	88	69	12	171	186	114	61	85	34
Chrysophyceae																		
Dinobryon	7	14	10	13	24	p								6				
Sub-total	7	14	10	13	24	p								6				
Bacillariophyceae																		
Synedra		p	1	1	2	1					1	2						1
Melosira		3	3	21	15	28					2	2		10	4	p	2	2
Cyclotella	1	2	p		p	1			2	20	3	1	3	1	2	9	8	p
Asterionella	1	10	3	8	11	8		14		p	50	18	7			p		4
Navicula	p			p														
Tabellaria	17		7	10	4				16		3	p	19		35		7	3

Table 3. continued......

	June 14						August 3						September 26					
	1	5	10	14	18	22	1	5	10	14	18	22	1	5	10	14	18	22
Bacillariophyceae(cont'd).																		
Diatoma																1		
Sub-total	19	15	14	40	32	38		14	18	20	59	23	29	11	41	10	17	10
Chlorophyceae																		
Staurastrum		2			p													
Dictyosphaerium					4													
Scenedesmus																	1	
Micractinium										11								
Ankistrodesmus	p														p			
Chlamydomonas	p	p	p	p	1	1												
Arthrodesmus	p	1	p									p					1	
Coelastrum												1						
Botryococcus													p				1	p
Ulothrix																2		
Stichococcus					1													
Chlorella		p	1															
Cosmarium		p																
Sub-total	p	3	1	p	6	1				11		1	p		p	2	3	p
Dinophyceae																		
Peridinium	p			p						2				p				
Sub-total	p			p						2				p				
TOTAL	26	33	25	53	62	39	95	149	128	121	128	36	200	203	155	73	105	44

APPENDIX B

Table 4. Summary of data on phytoplankton collected in Quirke Lake on three dates in 1966. Samples were collected at six depths to 30 metres. Results are expressed in areal standard units per millilitre.

	June 14						August 3						September 26					
	1	6	12	17	23	28	1	6	12	17	23	28	1	6	12	17	23	28
Myxophyceae																		
Anacystis																p		
Lyngbya	9	9	2	12	10	28	p	p	p	6	4	5				p		1
Gomphosphaeria																p		
Chrococcus		p	p	p														
Aphanizomenon															p			
Sub-total	9	9	2	12	10	28	p	p	p	6	4	5			p	p		1
Chrysophyceae																		
Dinobryon	2		p	6				p	3	2	3	6				1		p
Sub-total	2		p	6				p	3	2	3	6				1		p
Bacillariophyceae																		
Synedra																p		
Cyclotella	p	p	p	p									p			p		
Asterionella							p											
Navicula										p		p						
Stephanodiscus										p								
Sub-total	p	p	p	p			p			p		p	p			p		
Chlorophyceae																		
Mougeotia								p		2				1				
Actinastrum												1						
Ankistrodesmus											p							
Chlorella						p		p		p				p	p			

	June 14						August 3						September 26					
	1	6	12	17	23	28	1	6	12	17	23	28	1	6	12	17	23	28
Chlorophyceae(cont'd).																		
Cosmarium							p	p										
Staurastrum										p								
Crucigenia													p	p		p		
Tetraedron								p										
Chlamydomonas					p	1				p								
Sub-total					p	1	p	p		2	p	1	p	1	p	p		
Euglenophyceae																		
Trachelomonas									p									
Sub-total									p									
Dinophyceae																		
Peridinium							p	1					1	1	1	p		
Sub-total							p	1					1	1	1	p		
TOTAL	11	9	2	18	10	29	p	1	3	10	7	12	1	2	1	1		1

APPENDIX B

Table 5. Summary of data on phytoplankton collected in Pecors Lake on three dates in 1966. Samples were collected at six depths to 30 metres. Results are expressed in areal standard units per millilitre.

	June 29						August 17						September 28					
	1	5	10	14	18	22	1	5	10	14	18	22	1	5	10	14	18	22
Myxophyceae																		
Plectonema	p	1	1	p	p		p			3				p		1		3
Anacystis							p	p		p					p	2		
Aphanizomenon							p											
Sub-total	p	1	1	p	p		p	p		3				p	p	3		3
Chrysophyceae																		
Dinobryon	5	7	17	44	75		2			2				2	p	2		17
Sub-total	5	7	17	44	75		2			2				2	p	2		17
Bacillariophyceae																		
Achnanthes															p			
Cyclotella			p	2	p			p							p			p
Diatoma														3	p			1
Navicula			p											1				1
Synedra			p		p										p			
Cocconeis														p				
Surirella		p					p											
Melosira					p													
Nitzschia					p													
Tabellaria		p			3													
Stephanodiscus				p														
Pinnularia		p	p															
Sub-total		p	p	2	3		p	p						4	p			2

Table 5. continued.......

	June 29						August 17						September 28					
	1	5	10	14	18	22	1	5	10	14	18	22	1	5	10	14	18	22
Chlorophyceae																		
Chlamydomonas			p	p														
Chlorella							p									p		
Closterium	p						p	p	p	p								
Mougeotia							p			p					2			
Oocystis														p	p	p		
Scenedesmus		p	p													p		
Sphaerocystis														6	3			4
Staurastrum																		p
Tetraedron																p		
Sub-total	p	p	p	p			p	p	p	p				6	5	p		4
Euglenophyceae																		
Euglena		p																
Dinophyceae																		
Peridinium	p	p	p	1	p		p	p		p						p		1
Sub-total	p	p	p	1	p		p	p		p						p		1
TOTAL	5	8	18	47	78		2	p	p	5				12	5	5		27

APPENDIX C

APPENDIX C

Table 1a. Results of chemical determinations (mg l^{-1} except pH) made on water samples collected to 31 and 39 metres in Dunlop and Quirke Lakes on June 17, 1965. Values of phosphorus are expressed in mg PO_4 l^{-1}, total Kjeldahl nitrogen (including ammonia) and nitrate as mg N l^{-1}, and orthosilicate as mg SiO_2 l^{-1}.

	Dunlop Lake								Quirke Lake							
	1	5	10	14	18	22	27	31	1	6	12	17	23	28	34	39
pH	6.5	6.8	6.6	6.6	6.5	6.4	6.4	6.4	5.5	5.6	5.5	5.3	5.3	5.3	5.3	5.3
Ca^{+2}	4.8	7.8	6.4	4.8	5.6	6.4	4.8	6.4	42	54	53	46	44	49	45	46
SO_4^{-2}	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	82	69	82	84	79	97	91	80
NO_3^{-1}	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	3.00	3.60	3.40	3.00	3.00	2.20	5.50	3.20
Tot. Diss. Solids	18	12	12	20	36	10	28	30	242	224	232	-	246	224	-	228
Tot.P	.02	.02	.02	.04	.03	.04	.02	.13	.04	.03	.02	.03	.03	.02	.02	.02
Tot. Kjel.N.	.33	.26	.26	.33	.26	.84	.84	.71	1.30	1.35	1.00	1.30	1.10	1.30	1.20	1.00

APPENDIX C

Table 1b. Results of chemical determinations (mg l^{-1} except pH) made on water samples collected to 31 and 39 metres in Dunlop and Quirke Lakes on August 10, 1965. Values of phosphorus are expressed in mg PO_4 l^{-1}, total Kjeldahl nitrogen (including ammonia) and nitrate as mg N l^{-1}, and orthosilicate as mg SiO_2 l^{-1}.

	Dunlop Lake								Quirke Lake							
	1	5	10	14	18	22	27	31	1	6	12	17	23	28	34	39
pH	6.2	6.4	6.5	6.6	6.5	6.4	6.4	6.4	5.6	5.6	4.6	5.0	5.3	5.5	8.5	7.1
Ca^{+2}	5	4	4	4	4	5	4	4	40	41	40	44	42	42	44	44
SO_4^{-2}	10	10	10	10	9	9	9	9	210	210	210	214	214	221	221	221
NO_3^{-1}	.00	.05	.00	Tr.	.10	.10	.12	.14	3.00	3.50	2.50	3.50	3.50	4.00	4.00	4.00
Tot. Diss. Solids	30	14	28	18	38	30	26	12	234	200	278	258	254	292	250	248
Tot.P	.03	.04	.04	.02	.06	.04	.04	.04	.02	.04	.04	.04	.04	.02	.04	.04
Tot. Kjeld.N.	.13	.07	.07	.26	.13	.13	.07	.07	1.40	1.40	1.10	1.20	1.20	1.20	1.40	1.20

APPENDIX C

Table 1c. Results of chemical determinations (mg l^{-1} except pH) made on water samples collected to 31 and 39 metres in Dunlop and Quirke Lakes on October 2, 1965. Values of phosphorus are expressed in mg PO_4 l^{-1}, total Kjeldahl nitrogen (including ammonia) and nitrate as mg N l^{-1}, and orthosilicate as mg SiO_2 l^{-1}.

	Dunlop Lake								Quirke Lake							
	1	5	10	14	18	22	27	31	1	6	12	17	23	28	34	39
pH	8.1	7.9	7.9	7.8	7.5	7.1	7.1	6.9	6.0	5.9	5.9	6.9	5.9	5.8	5.7	5.8
Ca^{+2}	5	5	5	5	4	5	2	4	40	40	40	41	42	44	44	44
Mg^{+2}	10	8	6	7	10	8	8	4	8	8	9	-	7	7	6	6
Na^{+1}	0.2	0.2	0.2	0.4	0.2	0.3	0.5	0.2	5.2	5.0	4.6	4.5	6.9	5.4	6.9	6.5
K^{+1}	0.5	0.5	0.5	0.9	0.6	0.6	0.7	0.8	5.5	5.5	5.0	5.4	-	5.0	4.7	5.1
SO_4^{-2}	2	4	4	0	6	6	4	4	103	80	73	118	119	116	95	116
Cl^{-1}	2	2	2	2	2	2	2	2	8	7	7	8	15	8	8	8 ?
NO_3^{-1}	Tr.	0.00	0.00	0.00	Tr.	Tr.	.10	.10	4.00	4.00	4.00	5.00	3.00	5.00	5.00	4.00
Tot.Diss. Solids	16	14	4	4	12	4	4	4	190	182	204	200	240	230	240	238
Tot.P	.12	.04	.08	0	.08	.08	0	0	.12	.08	.04	.08	0	.16	.04	.04
Tot. Kjeld.N.	.07	.07	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	1.20	1.30	1.20	1.30	1.10	1.20	1.30	1.30

APPENDIX C

Table 2a. Results of chemical determinations (mg l^{-1} except pH) made on water samples collected to 23 and 30 metres in Dunlop and Quirke Lakes on June 14, 1966, and Pecors Lake on June 29, 1966. Values of phosphorus are expressed in mg PO_4 l^{-1}, total Kjeldahl nitrogen (including ammonia) and nitrate as mg N l^{-1}, and orthosilicate as mg SiO_2 l^{-1}.

	Dunlop Lake						Quirke Lake						Pecors Lake					
	1	5	10	14	18	22	1	6	12	17	23	28	1	5	10	14	18	22
pH	6.9	6.9	6.8	6.4	6.6	6.6	5.3	5.3	5.1	5.1	5.1	5.1	7.3	6.3	6.1	6.1	6.1	6.0
Ca^{+2}	2	4	3	4	3	3	36	36	36	38	36	38	58	56	65	78	85	89
SO_4^{-2}	7	9	19	10	10	6	103	103	107	107	108	100	165	155	184	220	242	252
NO_3^{-1}	.05	.05	.06	.05	.05	.06	4.00	3.00	2.00	1.50	3.00	3.00	2.50	3.75	3.75	6.25	7.50	5.00
Tot.Diss. Solids	30	26	38	18	36	24	206	180	220	194	192	210	353	345	400	456	478	499
Tot.P.	.00	.00	.00	.00	.02	.00	.00	.00	.00	.00	.00	.22	.01	.02	.00	.00	.00	.00
Tot.Kjel. N.	1.20	.13	.07	.26	.07	.07	1.15	1.20	1.30	1.10	1.10	1.20	1.80	1.80	1.95	2.60	2.30	2.45
Ortho-silicate	1.00	1.00	1.08	1.20	1.32	1.36	*	*	*	*	*	*	3.44	3.76	3.52	3.76	2.08	4.32

* sample exhausted

APPENDIX C

Table 2b. Results of chemical determinations (mg l^{-1} except pH) made on water samples collected to 23 and 30 metres in Dunlop and Quirke Lakes on August 3, 1966 and Pecors Lake on August 17, 1966. Values of phosphorus are expressed in mg PO_4 l^{-1}, total Kjeldahl nitrogen (including ammonia) and nitrate as mg N l^{-1}, and orthosilicate as mg SiO_2 l^{-1}.

	Dunlop Lake						Quirke Lake						Pecors Lake					
	1	5	10	14	18	22	1	6	12	17	23	28	1	5	10	14	18	22
pH	8.2	8.0	7.9	7.8	7.6	7.5	6.3	6.0	6.1	6.1	5.9	5.6	6.7	6.9	6.8	6.5	6.2	6.0
Ca^{+2}	4	4	4	4	3	4	38	38	40	40	39	38	57	57	50	81	87	90
Mg^{+2}													3	4	14	6	6	7
Na^{+1}													6.0	6.0	6.0	7.0	8.0	8.0
K^{+1}													7.0	7.0	8.0	9.0	10.0	11.0
SO_4^{-1}	11	9	10	12	8	10	98	91	88	88	91	98	19	19	20	196	230	246
Cl^{-1}													10	9	11	13	13	14
NO_3^{-1}	.01	.01	.01	.01	.01	.18	2.20	2.80	3.20	2.60	3.20	3.20	2.50	3.00	3.00	4.00	3.50	4.50
Tot.Diss. Solids	26	48	24	32	34	44	208	200	220	212	202	214	308	314	326	486	436	486
Sol.P.	.00	.04	.00	.02	.00	.02	.02	.00	.00	.00	.00	.00	.02	.00	.00	.00	.00	.00
Tot.P.	.20	.08	.02	.04	.00	.04	.02	.00	.00	.00	.00	.00	.03	.00	.00	.00	.01	.00
Tot. Kjeld.N.	.20	.20	.07	.07	.13	.20	1.30	1.40	1.30	1.40	1.20	1.20	1.65	1.65	2.10	3.80	1.50	1.35

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Table 2c. Results of chemical determinations (mg l^{-1} except pH) made on water samples collected to 23 and 30 metres in Dunlop and Quirke Lakes on September 26, 1966 and Pecors Lake on September 28, 1966. Values of phosphorus are expressed in mg PO_4 l^{-1}, total Kjeldahl nitrogen (including ammonia) and nitrate as mg N l^{-1}, and orthosilicate as mg SiO_2 l^{-1}.

	Dunlop Lake						Quirke Lake						Pecors Lake					
	1	5	10	14	18	22	1	6	12	17	23	28	1	5	10	14	18	22
pH	6.9	7.2	7.7	7.2	6.7	6.6	6.3	5.9	5.6	5.8	5.3	5.2	6.3	-	6.4	5.8	5.5	5.5
Ca^{+2}	4	4	4	4	5	2	38	38	38	40	40	39	59	-	60	83	87	91
Mg^{+2}	1	1	1	0	1	1	4	4	3	3	2	4	-	-	-	-	-	-
Na^{+1}	0.8	0.8	0.6	0.6	0.9	0.8	4.6	4.7	3.9	4.5	4.6	4.9	-	-	-	-	-	-
K^{+1}	0.4	0.3	0.3	0.3	0.3	0.3	5.6	5.8	4.2	5.6	5.7	6.1	-	-	-	-	-	-
SO_4^{-2}	6	5	6	7	7	6	73	73	-	78	-	73	128	-	128	215	188	208
Cl^{-1}	3	2	2	5	2	2	7	7	7	8	7	7	-	-	-	-	-	-
NO_3^{-1}	.00	.00	.00	.00	.03	.03	3.00	3.50	3.00	2.50	3.00	4.00	3.00	-	3.00	4.00	4.50	4.50
Tot.Diss. Solids	33	25	27	45	43	26	213	227	201	222	202	230	287	-	279	387	457	423
Sol.P	.00	.00	.00	.00	.00	.01	.00	.00	.00	.00	.00	.00	-	-	-	-	-	-
Tot.P	.01	.00	.02	.02	.01	.01	.00	.00	.00	.00	.00	.00	.01	-	.00	.02	.00	.02
Tot. Kjeld.N.	.07	.07	.07	.07	.07	.07	1.10	1.10	1.10	1.05	1.15	1.15	1.35	-	1.35	2.30	1.95	2.20
SiO_2	-	-	-	-	-	-	-	-	-	-	-	-	0.98	-	0.98	2.20	3.20	1.60

APPENDIX C

Table 3a. Results of chemical determinations (mg l^{-1} except pH) made on water samples collected to 23 and 30 metres in Dunlop, Quirke and Pecors Lakes on May 16 and 17, 1967. Values of phosphorus are expressed in mg PO_4 l^{-1}, total Kjeldahl nitrogen (including ammonia) and nitrate as mg N l^{-1}, and orthosilicate as mg SiO_2 l^{-1}.

	Dunlop Lake						Quirke Lake						Pecors Lake			
	1	5	10	14	18	22	1	6	12	17	23	28	1	5	10	14
pH	6.9	6.9	7.0	6.9	7.1	7.0	6.0	6.0	5.9	6.0	5.8	5.8	6.5	6.4	6.5	6.3
Ca^{+2}	4	3	3	3	3	3	34	34	34	34	34	34	42	38	42	42
SO_4^{-2}	6	5	5	5	5	5	73	82	82	73	76	80	110	114	114	-
NO_3^{-1}	.10	.10	.10	.15	.15	.10	2.00	2.50	2.50	2.00	2.00	2.50	1.70	1.60	2.50	3.50
Tot.Diss. Solids	2	8	9	6	8	32	98	73	84	75	78	88	270	348	289	378
Sol.P	.03	.02	.02	.02	.02	.02	.01	.01	.01	.01	.01	.01	.03	.04	.02	.02
Tot.P	-	.02	.02	.02	.02	-	.01	.01	.01	.01	.01	.01	.03	.04	.02	.02
Tot.Kjeld. N.	.46	.64	.46	.52	.77	1.50	1.50	1.95	1.65	1.45	1.65	1.65	2.60	3.00	2.80	2.80

APPENDIX C

Table 3b. Results of chemical determinations (mg l^{-1} except pH) made on water samples collected to 23 and 30 metres in Dunlop, Quirke and Pecors Lakes on June 6, 1967. Values of phosphorus are expressed in mg PO_4 l^{-1}, total Kjeldahl nitrogen (including ammonia) and nitrate as mg N l^{-1}, and orthosilicate as mg SiO_2 l^{-1}.

	Dunlop Lake						Quirke Lake						Pecors Lake					
	1	5	10	14	18	22	1	6	12	17	23	28	1	5	10	14	18	22
pH	6.3	6.5	6.5	6.6	6.6	6.6	6.0	5.7	5.7	5.4	5.3	5.2	6.1	6.2	6.2	7.1	5.8	5.7
Ca^{+2}	4	4	4	4	4	4	34	34	34	34	35	36	54	39	61	77	80	78
SO_4^{-2}	10	10	10	10	9	9	86	88	87	86	89	88	120	96	144	92	92	93
NO_3^{-1}	.10	.10	.10	.15	.10	.10	2.50	2.50	4.00	5.00	3.00	3.00	4.00	4.00	5.00	5.00	5.00	5.00
Tot.Diss. Solids	21	29	15	19	11	9	175	179	161	259	183	167	246	169	99	355	367	391
Sol. P.	.09	.00	.02	.07	.12	.08	.31	.01	.01	.01	.01	*	.06	.04	.09	.28	.06	.02
Tot.P	.20	.01	.20	.25	.20	.08	.35	.01	.09	.09	.10	*	.06	.05	.09	.56	.07	.05
Tot.Kjeld. N.	.39	.33	.33	.26	.26	.33	1.2	1.0	1.3	1.2	1.3	1.4	2.40	1.80	2.60	2.80	2.60	2.20

* Sample exhausted

APPENDIX C

Table 3c. Results of chemical determinations (mg l^{-1} except pH) made on water samples collected to 23 and 30 metres in Dunlop, Quirke and Pecors Lakes on June 27, 1967. Values of phosphorus are expressed in mg PO_4 l^{-1}, total Kjeldahl nitrogen (including ammonia) and nitrate as mg N l^{-1}, and orthosilicate as mg SiO_2 l^{-1}.

	Dunlop Lake						Quirke Lake						Pecors Lake					
	1	5	10	14	18	22	1	6	12	17	23	28	1	5	10	14	18	22
pH	6.7	7.0	7.1	6.9	6.8	6.7	5.5	5.7	5.3	5.3	5.3	5.3	6.2	6.2	6.1	5.8	5.9	5.7
Ca^{+2}	5	5	5	5	6	5	34	34	35	35	35	37	56	45	69	78	83	82
SO_4^{-2}	Tr.	0	0	0	Tr.	Tr.	104	97	101	101	101	101	102	120	173	200	213	206
Cl^{-1}	2	2	2	2	2	2	6	6	7	6	6	8	8	7	11	13	13	12
NO_3^{-1}	.05	.07	.10	.12	.15	.15	*	*	*	*	*	*	*	*	*	1.75	1.75	1.60
Tot.Diss. Solids	-	30	72	66	32	48	254	246	236	252	226	270	236	260	358	430	378	434
Sol.P	-	.15	.14	.13	.21	.16	.09	.07	.10	.10	.09	.10	.25	.14	.11	.08	.07	.10
Tot.P.	.30	.40	.50	.70	*	*	*	*	*	*	*	.40	*	*	*	*	*	*
Tot.Kjeld. N.	*	*	*	*	1.15	0.07	1.65	1.15	1.10	1.15	1.30	*	0.95	1.50	0.99	2.20	1.40	2.45
SiO_2	.59	.59	.56	.59	.84	.76	.53	.79	.73	.70	.56	.56	.64	.70	.64	.67	.62	.56

* Sample exhausted

Table 3d. Results of chemical determinations (mgL^{-1} except pH) made on water samples collected to 23 and 30 metres in Dunlop, Quirke and Pecors Lakes on July 14 and 15, 1967. Values of phosphorous are expressed in mg PO_4 l^{-1}, total Kjeldahl nitrogen (including ammonia) and nitrate as mg N l^{-1}, and orthosilicate as mg SiO_2 l^{-1}.

	1	5	10	14	18	22	1	6	12	17	23	28	1	5	10	14	18	22
pH	6.4	6.3	6.3	-	6.7	7.4	5.3	5.5	*	*	6.2	6.1	7.6	7.2	7.4	7.4	7.4	7.2
Ca^{+2}	-	-	-	-	4	3	34	34	*	*	*	*	85	-	-	-	-	-
SO_4^{-2}	-	-	-	-	-	-	85	84	*	*	214	220	220	-	-	-	-	-
Cl^{-1}	8	8	9	-	6	6	6	6	6	6	12	12	13	-	-	-	-	-
NO_3^{-1}	-	-	-	-	-	-	2.25	3.40	*	*	1.50	1.70	1.50	-	-	-	-	-
Tot.Diss. Solids	-	-	-	-	-	-	147	*	132	127	*	*	412	-	-	-	-	-
Sol.P.	.08	.04	.05	-	.01	.01	.02	.01	.02	.01	.04	.05	.06	.06	.05	.04	.04	.07
Tot.P	*	*	*	-	*	*	.03	*	.03	.01	*	*	*	*	*	*	*	*
Tot. Kjeld.N.	0.91	1.95	2.50	-	1.30	*	1.20	1.20	*	*	3.10	3.10	2.20	0.39	0.26	0.33	0.39	0.43
SiO_2	.84	.84	.88	-	0.93	1.02	.64	.62	*	*	.90	.90	-	-	-	-	-	-

* Sample exhausted

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Table 3e. Results of chemical determinations (mgl^{-1} except pH) made on water samples collected to 23 and 30 metres in Dunlop, Quirke and Pecors Lakes on July 27 and 28, 1967. Values of phosphorous are expressed in mg PO_4 l^{-1}, total Kjeldahl nitrogen (including ammonia) and nitrate as mg N l^{-1}, and orthosilicate as mg SiO_2 l^{-1}.

	Dunlop Lake						Quirke Lake						Pecors Lake					
	1	5	10	14	18	22	1	6	12	17	23	28	1	5	10	14	18	22
pH	6.7	6.6	6.6	6.5	5.6	5.4	6.5	5.3	5.2	5.2	5.3	5.2	6.2	6.0	5.6	5.4	6.4	6.5
Ca^{+2}	3	4	3	4	4	3	34	34	35	35	35	35	42	44	57	63	80	82
SO_4^{-2}	10	8	9	7	7	8	85	88	91	87	88	89	158	153	140	156	193	200
Cl^{-1}	12	12	2	2	2	1	–	–	6	6	6	6	–	19	7	7	9	10
NO_3^{-1}	.04	.00	.02	.04	.05	.22	2.20	2.40	3.40	2.25	3.00	2.80	1.35	1.35	1.75	1.10	1.10	2.00
Tot.Diss. Solids	15	*	15	17	27	19	169	152	–	152	151	158	199	183	187	*	*	374
Sol. P.	.01	.00	.01	.02	.04	.01	.02	.01	.05	.04	.01	.01	.04	.00	.01	.01	.01	.00
Tot.P.	.01	*	.02	.03	.04	.01	.02	.01	.06	*	.02	.01	.05	.00	.01	.02	.01	.00
Tot.Kjeld. N.	.58	.20	.39	.84	.98	1.20	1.65	1.50	1.30	1.20	1.10	1.20	1.40	1.50	2.10	2.60	2.45	2.30
SiO_2	.82	.79	.70	.70	.70	.64	.53	.59	.67	.59	.56	.56	.64	.70	.79	.79	.76	.76

* Sample exhausted

APPENDIX C

Table 3f. Results of chemical determinations (mg l^{-1} except pH) made on water samples collected to 23 and 30 metres in Dunlop, Quirke and Pecors Lakes, on August 29, and 31, 1967. Values of phosphorous are expressed in mg PO_4 l^{-1}, total Kjeldahl nitrogen (including ammonia) and nitrate as mg N l^{-1}, and orthosilicate as mg SiO_2 l^{-1}.

	Dunlop Lake						Quirke Lake						Pecors Lake					
	1	5	10	14	18	22	1	6	12	17	23	28	1	5	10	14	18	22
pH	7.8	8.1	8.0	7.9	7.7	7.6	8.2	6.5	6.1	8.1	5.6	5.4	7.2	7.1	7.8	8.1	5.6	5.6
Ca^{+2}	5	4	5	4	5	5	34	34	36	35	35	35	45	45	80	82	84	83
SO_4^{-2}	26	11	7	7	7	7	82	82	83	*	82	83	102	102	204	204	202	202
Cl^{-1}	2	1	1	1	1	1	5	6	6	6	6	6	7	7	11	11	12	12
NO_3^{-1}	.40	-	.50	.30	.40	.50	2.00	3.00	2.50	3.00	3.00	1.60	-	-	3.00	4.60	3.00	4.00
Tot.Diss. Solids	18	13	24	31	14	24	144	152	160	154	142	168	-	-	340	322	362	380
Sol.P.	*	.03	.01	.03	.02	.02	.01	.01	.02	*	.01	.01	.01	.01	.02	.01	.16	.02
Tot.P.	.05	.07	.06	.06	*	.06	.02	.01	.04	.03	.03	.03	*	*	.05	.01	.59	.02
Tot.Kjeld. N.	.58	.65	.65	.58	.52	.65	1.50	1.65	1.10	1.60	1.40	1.25	1.65	1.65	2.02	1.80	2.02	2.02
SiO_2	1.0	1.1	0.8	1.1	1.4	1.4							2.1	2.1	2.1	2.1	1.8	1.9

* Sample exhausted

APPENDIX C

Table 3g. Results of chemical determinations (mg l^{-1} except pH) made on water samples collected to 23 and 30 metres in Dunlop Quirke and Pecors Lakes on September 13, 1967. Values of phosphorous are expressed in mg PO_4 l^{-1} total Kjeldahl nitrogen (including ammonia) and nitrate as mg N l^{-1}, and orthosilicate as mg SiO_2 l^{-1}.

	Dunlop Lake						Quirke Lake						Pecors Lake					
	1	5	10	14	18	22	1	6	12	17	23	28	1	5	10	14	18	22
pH	8.5	8.4	8.2	6.6	6.7	6.5	5.9	5.7	5.5	5.4	*	6.8						
Ca^{+2}	4	3	4	4	4	4	35	35	35	36	36	86						
SO_4^{-2}	9	12	8	7	7	7	98	100	94	98	98	100						
Cl^{-1}	3	1	1	1	1	1	5	5	5	6	6	5						
NO_3^{-1}	30	.40	.40	.30	.30	.40	2.50	2.50	0.75	0.75	*	2.50						
Tot.Diss. Solids	30	31	35	37	31	30	158	158	168	180	178	170						
Sol.P.	.01	.06	.01	.01	.02	.01	.01	.01	.01	.01	.09	.03						
Tot.P.	.19	.17	.04	.07	.05	.16	.05	.02	.02	*	.14	.03						
Tot.Kjeld. N.	*	*	.52	.73	.65	1.00	*	2.80	2.80	2.20	2.80	2.80						

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Table 3h. Results of chemical determinations (mg l^{-1} except pH) made on water samples collected to 22 and 28 metres in Dunlop, Quirke and Pecors Lakes on October 2 and 3, 1967. Values of phosphorous are expressed in mg PO_4 l^{-1}, total Kjeldahl nitrogen (including ammonia) and nitrate as mg N l^{-1} and orthosilicate as mg SiO_2 l^{-1}.

	Dunlop Lake						Quirke Lake						Pecors Lake					
	1	5	10	14	18	22	1	6	12	17	23	28	1	5	10	14	18	22
pH	8.5	8.7	8.6	8.4	7.4	7.4	6.5	6.3	6.3	6.2	6.0	6.0	6.0	6.1	6.1	5.9	7.5	7.2
Ca^{+2}	3	4	4	4	4	4	35	35	36	35	36	36	47	46	48	83	84	84
SO_4^{-2}	6	6	6	6	6	6	102	98	96	96	100	99	121	120	121	216	228	228
NO_3^{-1}	.10	.10	.10	.20	.20	.20	*	2.00	2.00	2.50	2.00	2.00	2.00	2.00	2.00	2.50	3.00	2.50
Tot.Diss. Solids	18	16	14	14	22	20	172	184	170	178	166	162	214	226	216	362	388	382
Sol. P.	.01	.02	.01	.01	.02	.01	.01	.01	.01	.01	.01	.01	.01	.01	.02	.12	.01	.01
Tot. P.	.04	.03	.03	.04	.06	.04	.03	.03	.03	.04	.03	.03	.07	.02	.03	.49	.13	.04
Tot.Kjeld. N.	.26	.13	.26	.13	.46	.26	3.30	6.60	5.00	8.30	6.60	*	6.60	8.30	*	*	9.90	9.90